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DESIGN AND EVALUATION OF A CHAMBER CAPABLE OF CONTAINING THE DETONATION EFFECTS OF 40 POUNDS OF TNT

by

B. D. Trott,
J. E. Backofen, Jr.,
and
J. J. White, III

BATTELLE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

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A 5-foot-diameter, spherical blast containment chamber was designed for the repeated containment of 40-pound charges of TNT. The vessel included a reinforced access port 18 inches in diameter, closed by a pair of inward-swinging cafe doors which overlapped the port reinforcing ring all around the edges. Four vessels were built to this design. Two of the vessels, mounted on cradles identical to the trailer-mounted version, but without the trailers, were experimentally evaluated for their blast containment capability.

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A total of 14 charges was detonated in the first vessel. In the first shots, charges ranging from 10 pounds to 30 pounds of composition C-4 explosive were fired. The next 7 shots were repeated 35-pound spherical charges of composition C-4. The final shot in the first vessel was 47.5 pounds of 60 percent strength commercial dynamite. At the conclusion of this test series the vessel was still in good condition and had swelled an average of 1 percent over the vessel surface, as determined by a network of fiducial gage lengths. Venting of burning detonation products from the vessel port was initially fairly severe, but modifications to the closure greatly reduced this problem. The design of the remaining three vessel doors was further modified to reduce the venting problem.

Three repeated 35-pound charges were fired in the second vessel, producing an accumulated plastic strain of 0.6 percent average over the vessel surface. This is in exceilent agreement with the observed strain on the first vessel after three shots. The door modifications greatly reduced the venting flame, and on two of the three shots, little or no flame vented. Measured peak free-air blast overpressures successively decreased from 3.4 to 1.6 psi at 5 1/2 feet from the vessel port for the three shots. Likewise, the peak blast overpressures decreased from 0.95 to 0.53 psi at a distance of 13 1/2 feet from the port. This decrease is attributed to better seating of the doors being achieved by the blast loading.

Two vessels were mounted on modified, commercial, four-wheel trailers equipped with large tool boxes and shipped to NAVEODFAC for further evaluation as prototypes.

PREFACE

Mr. Lennard Wolfson of the Naval Explosive Ordnance Disposal Facility served as technical monitor for this program. The many helpful discussions with him materially aided the successful completion of this program. Several persons on the Battelle staff also made valuable contributions to this program. Worthy of mention are Joe H. Brown, Jr. for managerial support, H. W. Mishler for establishment and supervision of the welding procedures used in the fabrication of the containment vessels, A. S. Chace for technical support, W. H. Stefanov and others of the welding laboratory for conduct of the welding , J. W. Neutzling, H. C. Burchfield and others of the machine shop for fabrication and fit-up of the vessel, cradle, tool boxes and trailer modifications, W. F. Schola, and S. C. Green for assistance in the conduct of the explosive experiments and E. C. Nowell for the principal typing work.

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INTRODUCTION AND SUMMARY

This program was initiated to provide the armed services explosive ordnance disposal teams with a trailer-portable blast containment chamber capable of completely containing the blast from detonation of 40 lb of TNT or the equivalent, for several repetitions. The objectives of the work were to develop a vessel design, to fabricate and test prototypes to prove the blast containment capability, and to deliver two trailer-mounted prototype vessels to the Naval Explosive Ordnance Disposal Facility (NEODF) for further evaluation. To accomplish this objective, a spherical vessel design was developed which was predicted to suffer a fraction of one percent plastic strain, during blast containment. By designing the vessel to operate in the plastic strain regime, rather than providing sufficient vessel strength (and weight) to provide blast containment without plastic strain, a weight reduction probably in the neighborhood of 40% was achieved. The magnitude of the weight saving projected depends on the assumptions made regarding the maximum allowable elastic stresses and plastic strains. Obviously, a blast containment vessel designed for plastic deformation has a limited life, however for this portable application where few actual contained detonations are expected, the weight savings far outweigh the life limitation.

The vessel design developed utilized a 5-ft diameter spherical steel chamber with a 1.40-in. average wall thickness. The vessel was equipped with an 18-in. diameter access port as dictated by NEODF. The access port was arranged in a vertical plane, and closed by a pair of inward swinging, cafe-type doors which overlapped the access port on the inside.

A total of four vessels were constructed of ASTM A-537-72A Class 1 steel. Two of the vessels were proof-tested at Battelle Columbus Laboratories. The other two were mounted on specially modified trailers. After testing, all four vessels were delivered to NEODF.

The first vessel was extensively tested. A total of 13 detonations were contained in this vessel, of which 7 were 35-lb spherical charges of Composition C-4, and 1 was 47.5 lb of 60 percent strength dynamite in a spherical charge shape. At the conclusion of this test series, the vessel had suffered an average of about 1% plastic strain. Principally due to variations in wall thickness, the local strains on the vessel surface varied from 1.14 percent in the thinner regions (1.26-in. minimum wall thickness) to 0.77 percent in the thicker regions (1.52-in. maximum wall thickness). During the firing sequence the vessel strain hardened appreciably so that the final 35-lb C-4 shot of the series produced less than 1/3 the plastic strain produced by the first 35-lb shot. At the conclusion of the test series, the overall appearance of the vessel was essentially unchanged and the closure doors and hinges still operated satisfactorily, although the hinge mechanism suffered minor damage.

Subsequent vessels were fabricated with a minor change in the hinge design to eliminate the problem noted in the first vessel. Testing of the second vessel consisted of three firings of 35-lb spherical C-4 charges. The vessel strain after 3 shots was nearly identical to that of the first vessel after 3 shots, 0.6 percent strain.

At the conclusion of testing, the first vessel was shipped to NEODF. The other test vessel and two trailer-mounted vessels were shipped to NEODF at the conclusion of the program.

This report describes the material and vessel size selection criteria, fabrication procedures for all vessels, and the test procedures and results for the vessels tested.

VESSEL DESIGN AND FABRICATION

This section contains the design criteria for selection of the vessel size, the design criteria for the port reinforcing ring and door, the reasons for selection of the materials used, and a description of the fabrication method employed.

Vessel Size

The selection of the vessel size for this program was based on the predictions of a one dimensional, elastic-plastic analysis of a spherical vessel.[(1)*] This analysis was programmed in FORTRAN by Battelle[(2)] for evaluation of the maximum and residual plastic strains to be expected, in an in-house effort prior to the inception of this program. The vessel size was selected to be 5 ft in diameter with a 1.25-in. wall thickness. Using the conservative values of 50,000 psi for the material yield strength, in agreement with the material specification minimum 0.2 percent offset yield strength and the blast wave parameters of 50/50 Pentolite on a 1:1 equivalence to TNT, the selected vessel was predicted to strain 0.46 percent per 40-lb TNT shot. In practice, the hemispherical heads for the vessels were ordered to be a specified 1-1/8-in. minimum wall thickness with expectation of obtaining near the desired average wall thickness. As shown in the evaluation section of this report, the actual minimum and average wall thicknesses for the one vessel surveyed were 1.29- and 1.40-inches respectively.

Later estimates of the proper yield strength to be used for this A-537 Class 2 material suggested that 100,000 psi would more closely predict the vessel performance. Also, during the course of this program, the effects of the confined explosion gas pressure were added to the programmed analysis. Appendix A comprises copies of the computer output for the minimum, average, and maximum wall thickness cases for comparison with experiment.

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* References are given at the end of the report.

Reinforcing Ring and Door Design

The reinforcing ring for the 5.0-ft diameter vessel was initially sized using the thin-ring approximation[3] given in Appendix B as Equation (B-6). However, the final sizing was based upon Equation (B-8) of Appendix B since the thick ring approximation was more appropriate due to the small diameter of the vessel opening. The basic trapezoidal shape of the ring cross-section was then arrived at through an engineering layout on which the design procedure outlined in Appendix B was applied.

The design of the ring was further complicated by the fact that the closure consists of two semicircular doors. In the analysis of the effect of using two semicircular plates to close the circular opening, it was assumed that a static pressure load was distributed uniformly over the area of each door and that support of each door is only provided around its curved edge. The difference in the geometrical centers of the door area and the door circular arc then introduces a moment that prescribes that the bearing stress between the ring and a door is a maximum near the straight line separation of the two doors. This maximum bearing stress was then used to size the bearing surface between the ring and the doors.

The separation of a circular closure piece into two semicircular doors introduces a bending moment about the plane of the ring at the junction of the two doors and the ring since the center of the applied pressure moves from the symmetrical center location to the center of area of each of the doors. Since there are two doors and two sides to the ring, the moment applied on one side of the ring is found by multiplying the pressure over the area of the door by the distance from the center of the area to the straight edge of the semicircular door. The stress concentration produced by this moment over the loading in the ring from the sphere and an assumed circular closure piece was alleviated by welding doublers to the ring and sphere. The doublers were sized to match the maximum use of the spherical cap removed from the sphere for the entry port.

Equation (B-5) of Appendix B was used to ballpark the thickness of a one-piece circular door for the vessel port. Evaluation of this equation for $\nu = 0.27$, $a_s = 30.625$ inches, $t_s = 1.25$ inches (the calculated average sphere thickness on order from Lukens) and $a_o = 9.88$ inches (the approximate effective radius of the door to the bearing area on the reinforcing ring) leads to a lower bound door thickness of 3.28 inches.

However, for the split door configuration planned, the structure whose stress analysis is desired is a semicircular plate, and loaded with a uniform load per unit surface area. As the solution for this exact problem could not be located in the standard stress analysis sources, the solutions for two similar problems which serve to bound the exact problem adequately were located. A simply supported square plate under a uniform pressure is cut into two rectangular sections called half-square. The following formula was derived for the thickness[4] t_{sd} required for the square plate

$$t_{sd} = \left[8\beta t_s a_o / a_s^2 \right]^{1/2} \quad , \qquad (1)$$

where β is constant dependent on the ratio of the plate length to width. For this ratio equal to 1, $\beta = 0.2874$. For the half-square, the formula for the thickness[5] t_{hs} is identical to Equation (1), but the constant β is equal to 0.36. Thus the ratio of the two thicknesses will show the additional increment required when the square door is cut in half:

$$t_{hs}/t_{sd} = \left[0.36/0.2874 \right]^{1/2} = 1.12 \quad .$$

In like manner, the design criteria for the circular door was modified by applying the factor of 1.12. Thus the total thickness of the plate required is 3.67 inches, which was reduced to 3.50 inches for ordering and as an approximation.

Door Hinge Mechanism Design

The door hinge was designed to satisfy the following general criteria:

- Each door should have a well-defined axis of rotation that does not change while the door is subjected to handling or traveling loads.
- The pin support system should allow the ring and door to deflect and move during explosive loading so that neither the pin nor any of the mechanism's pieces fail.

The detail design that was chosen to satisfy these two criteria consisted of a spring loaded hinge that utilized a floating conical bearing to provide the necessary alignment of the door and yet allow lightly restrained movement during explosive loading. The angle on the conical bearing and the size of the hinge were determined from an engineering layout of the ring and the door. Due attention was paid to the clearance of the straight edge of the semicircular doors and the accessability to the hinge mechanism from the outside of the vessel port so that repairs and torquing of the bolts would be facilitated.

A spring load of one thousand pounds was determined to be required to keep the doors in proper alignment for 6 g traveling loads. Since this design was the first of its generic type, a radial clearance on the mechanism's bolt and bearing of 3/16 inch were allowed. The belleville springs that provided the preload in the mechanism were sized so that they would not bottom out before the bolt and bearing contacted the inside of the hinge.

Vessel Support Cradle Design

A basic loading of 6 g's in the vertical direction and 4 g's in any horizontal direction were used independently to size the following:

- Support feet attached to the vessel

- Tie down bolts between the vessel feet and the cradle
- Frame of the cradle
- Attachment points between the cradle and the trailer

Since this was an untried method of supporting an explosive containment vessel, the support surface between the vessel and the cradle was taken along a spherical radius so that the local restraint of the movement of the vessel wall would be minimized. The remainder of the design was concerned with firmly supporting and holding the vessel secure under the assumed handling and traveling loads.

Material Selection

The material selected for the vessel shells was a steel designated as ATSM-537-72A, Class 1, or ASME boiler steel SA-537A. This selection was made because of past good experience[3] with this grade of steel. Its original selection was based on five considerations: (1) a high level of toughness, as measured by the Charpy notched-bar impact test at low temperatures, (2) weldability, (3) cost, (4) availability, and (5) the fact that steels with good impact properties at low temperatures must be good quality steels. This provides additional assurance that deformation of the steels will not be adversely affected by unacceptable defects or improper processing.

ASTM A-537-72A, Class 1 steel is a higher quality carbon steel with a nominal composition of 0.15 to 0.2 percent carbon, 1.2 percent manganese, 0.2 percent silicon, less than 0.02 percent sulfur, and less than 0.01 percent phosphorus. This steel will have a minimum yield strength of 50,000 psi, a minimum ultimate strength of 80,000 psi, and a minimum of 18 percent elongation in 8 inches. In addition, this steel will have a guaranteed minimum Charpy notched-bar impact strength of value of 12 ft/lb at -75F. Nominal values for impact strength at -75 F are about 30 ft/lb and at -50 F about 55 ft/lb. The shells of all four vessels were constructed of this material.

During the time of fabrication of these vessels, U. S. economic conditions were such that steel availability was less than normal. After considerable difficulty forged material for all four doors and rings of ASTM-A-350, Class 3 material was located and ordered with an 8 week delivery time. At delivery time however, it turned out that material for only the four doors and two of the four required reinforcing rings was available. After additional difficulty, a large plate of 5-1/4-in.-thick, ASTM-537-72A, Class 2 (except for gage) material was located and purchased. The other two reinforcing rings were torch-cut and finish machined from this plate. The mechanical properties of both of these steel grades equal or exceed those of the vessel shell material.

The door hinge parts were constructed of mild steel or cold-rolled mild steel as were the mounting feet, supports and tie-down bolts. The cradles were constructed of standard structural grade 10-in. wide flange steel I-beams.

Fabrication and Welding

The vessels were procured as hot-pressed hemispheres with the edges machined as a weld preparation so that when two hemispheres were welded together they would form the best possible spheres.

After machining, the doors and hinge parts were assembled to the inner side of each reinforcement ring and the hinge-parts were welded in place. Each ring and door assembly was then welded into the port machined into one hemisphere. Finally the main girth weld joining the two hemispheres into a sphere was completed, the doubler plate welded in place, and lifting lugs and support feet were welded to the outside of the vessel. All of the vessel main structural welding was performed in the Battelle-Columbus Welding Development Laboratory using the established welding procedures included in Appendix C. Regardless of where the welding was performed, weld preheat temperature of at least 250 F was used.

The ring-to-vessel welds and main girth welds were made as follows, after preheat.

- The parts to be welded were tacked in place using E-8016-C3 covered electrode.
- The root pass was deposited from the vessel inside surface using the shielded metal arc process and E-8016-C3 covered electrode.
- The root head was ground out to sound metal from the outside.
- The ground surface of the root pass was dye-penetrant-inspected to insure removal of any lack of fusion in the base of the root pass. Areas showing any indication of lack of fusion were reground and rechecked until sound metal was ensured.
- The second weld pass was deposited from the outside by shielded metal arc using the same electrode material.
- The joints on the first vessel fabricated and subsequently tested extensively were completed using E70- S-4, 0.045-in.-dia. electrode wire in a semi-automatic metal-arc welding process, according to welding procedure specification P-74-A as given in Appendix C.
- The joints on the subsequent three vessels were completed using Hobart FabCO 81 cored wire electrode in a semi-automatic gas metal-arc welding process.
- The face of each pass was cleaned by power wire brushing to remove slag, and any visible porosity in the weld surface was removed by grinding to sound metals between welding passes.

- The completed joints were radiographically inspected in accordance with Section VIII, Pressure Vessel Division 1 of the ASME Boiler and Pressure Vessel Code, 1974.

For the girth welds, short lengths of 26-in.-dia. pipe were tacked to the vessel around the reinforcing ring and on the opposite side to allow rotation of the vessel on a fixture. This arrangement allowed automatic control of the welding advance speed and allowed all welds to be deposited in the flat or horizontal position.

The doubler plates were welded in position using the shielded metal arc process and E-8016-C3 covered electrode. These welds were not radiographed.

VESSEL EVALUATION

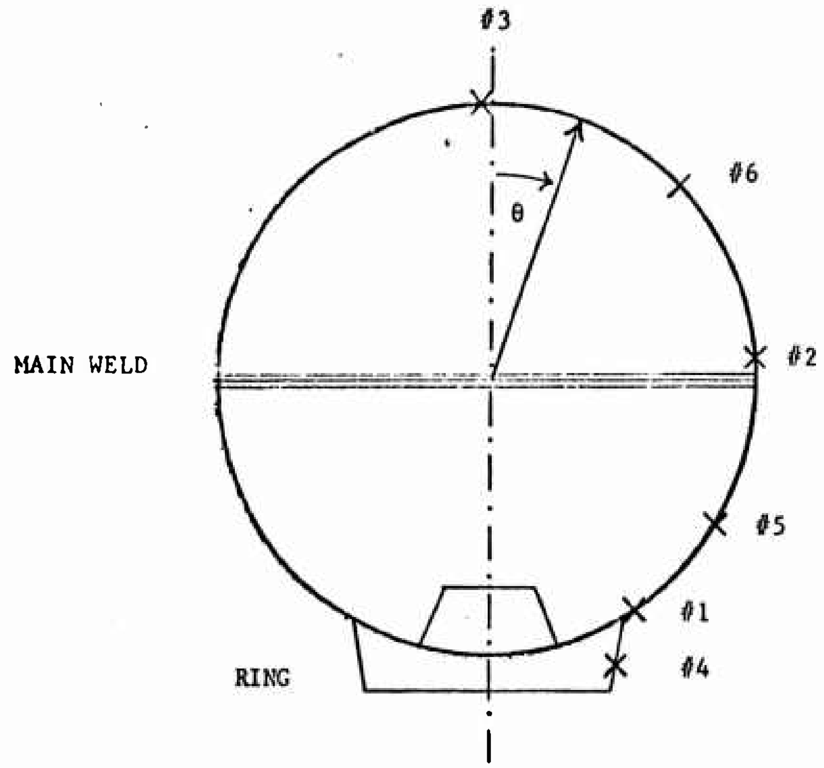
An essential feature of this program was the explosive testing of two of the four vessels fabricated. The first vessel tested had a port reinforcing ring of ASTM A-350 material, while the second vessel had a ring of ASTM A-537 Class 1 material. The results permitted an evaluation of the design criteria used, the methods of fabrication employed, and the explosive containment capability achieved. In addition to observation and inspection, instrumentation and measurements were useful for expressing the response of the vessels and for comparison with straightforward theoretical modeling of the vessel design and material. Establishment of a dependable model contributes to the confidence of achieving success with future designs to meet other choices of requirements. This section presents the results of extensive testing of the first vessel fabricated and brief testing of the second vessel.

Preliminary Work

Upon completion of the fabrication, the first 5-ft diameter explosive containment vessel and cradle were transported from the Battelle Laboratories in Columbus, Ohio to Building JS-6 of the Battelle Facilities at West Jefferson, Ohio. A total of six strain gages were installed on the right outside surface of the vessel in a horizontal plane that includes the polar axis, a horizontal line that is perpendicular to the plane of the door reinforcing ring and to the main equatorial weld of the two hemispheres. The location and orientation of the strain gages is given in Figure 1. Gage #4 was installed on the reinforcing ring to monitor hoop strains. The other five gages were distributed on the vessel surface between the ring weld (gage #1) and the pole (gage #3). The angular position of the gages with respect to the polar axis is specified in Figure 1. The arrangement of the strain gages assumes that the vessel response to explosive testing has cylindrical symmetry about the polar axis.

To install the strain gages, a clean surface was obtained using a portable grinder. The gages used were type EA-06-250-AE-350 manufactured by Micro-Measurements, Romulus, Michigan. They were specified to have a resistance of 350.0 ± 0.15% Ohms and a gage factor of 2.115 ± 0.5%. The strain gages were bonded to the vessel with EPY 500 epoxy manufactured by Baldwin-Lima-Hamilton (BLH). To cure the epoxy, the vessel was heated from the inside with a large portable natural gas burner mounted on the end of a 6-ft. pipe. ISA type K chromel-alumel thermocouples were spot welded near each strain gage to monitor the temperature. The epoxy was cured for at least one hour at 350 °F, as specified by BLH. A direct reading chart recorder was used to interpret the thermocouple outputs.

A series of fiducial marks were layed out on the vessel surface to monitor the average residual strain over 2-ft sections accumulated from plastic response to explosive testing. The marks consisted of punch impressions to locate one end of a specially constructed tool, scribe lines to align the tool and read the steel scale, and ink circles and numbers to locate and identify each mark. The location of the fiducial marks is indicated schematically in Figure 2. The distance between marks ranges from 22 to 25 inches.



TOP VIEW

GAGE NUMBER	θ	ORIENTATION
1	150.6°	Horizontal
2	86.2	Horizontal
3	-0.6	Horizontal
4	157.8	Hoop
5	122.6	Horizontal
6	44.8	Horizontal

FIGURE 1. LOCATION OF THE STRAIN GAGES INSTALLED ON THE OUTER SURFACE OF THE FIRST 5-FT. DIAMETER EXPLOSION CONTAINMENT VESSEL.

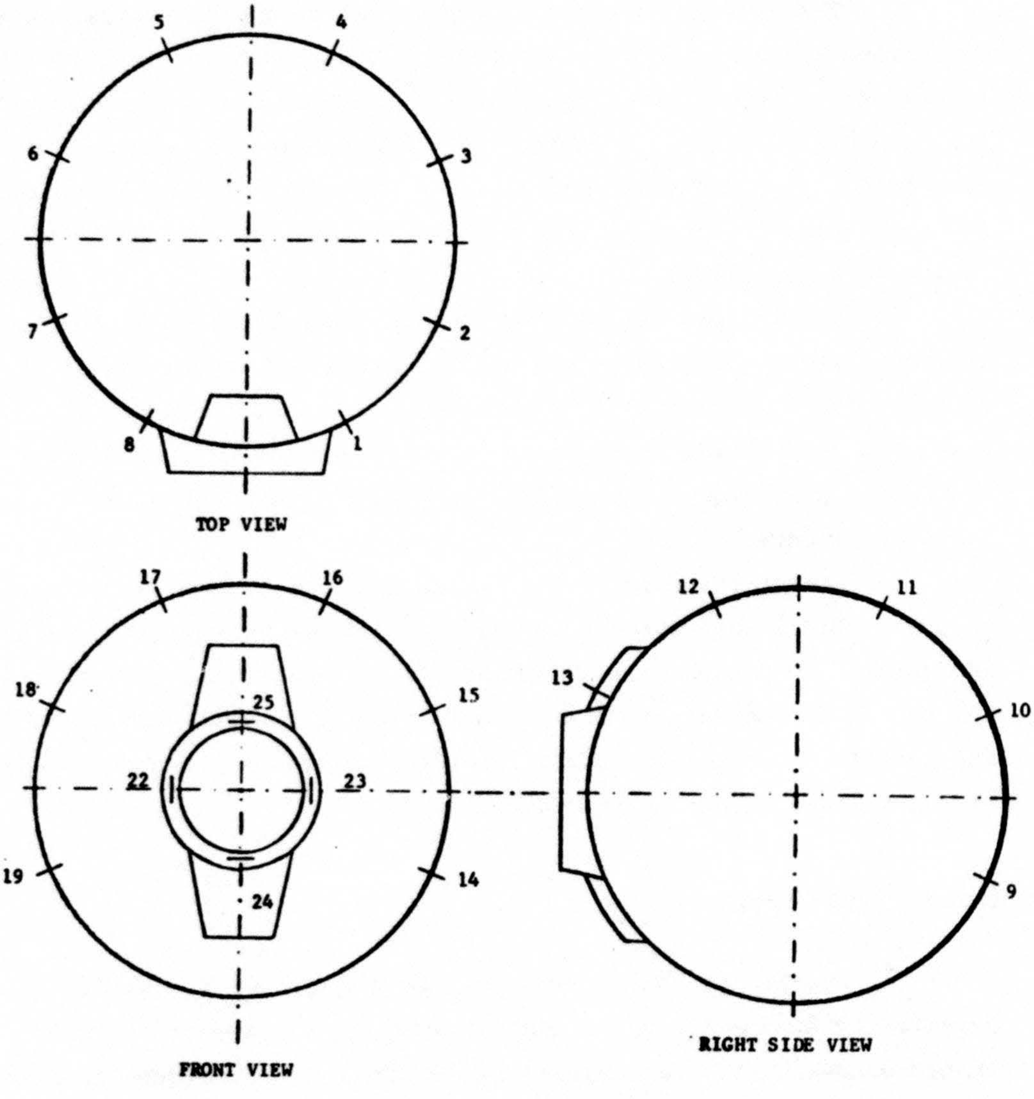


FIGURE 2. LOCATION OF FIDUCIAL MARKS ON THE FIRST 5-FT DIAMETER EXPLOSION CONTAINMENT VESSEL.

Instrumentation

The dynamic response of the vessel to explosive testing was determined by making Polaroid photographic pictures of oscilloscope traces of the output of bridge circuits containing a vessel strain gage as the active element. A Tektronix 502A dual beam oscilloscope gave records for gage numbers 1 and 2, and a Tektronix 5403 dual trace oscilloscope was used for gage numbers 3 and 4. Gage numbers 5 and 6 were not monitored dynamically.

The trigger for the oscilloscopes was provided by the explosion of the blasting cap used to set off the Detasheet at the center of the C-4 charge. The outward motion of the cap sheath made contact with an electrically isolated sheath of copper sheet taped to the cap, in order to close a circuit, discharge a capacitor, and produce a voltage pulse to trigger the scope sweeps.

Static readings of the strain gages were made with a Vishay Instruments Model SB-1 switch and balance unit and a Budd Model P-350 strain indicator. To determine the heating effect of the explosive charge, an ISA type K chromel-alumel thermocouple was spot welded near the pole of the vessel. A calibrated chart recorder was used to record the time-history of the voltage output of the thermocouple.

Charge Preparation

Charges of composition C-4 high explosives for shots 1-5 were prepared by hand packing a truncated cubical mold made of plywood. Pyramid shaped wooden blocks were placed in the corners of the cube to produce a shape that is a rough approximation to a sphere. An average density of 1.55 gm/cm^3 was achieved. A right circular cylinder of Detasheet, 1.5 inches in diameter, 1.5 inches long, and weighing approximately 0.14 pounds, was placed at the center of the charge. A cylindrical hole in the Detasheet cylinder and in one face of the C-4 charge permitted the insertion of a #8 commercial detonating cap at the time of explosive testing. The nominal dimension of the cubes was 6.0, 7.5, 8.1 and 8.6 inches for charges weighing 10, 20, 25, and 30 pounds, respectively.

For shots 6-13 improved spherical molds were fabricated using a combination of plaster and plywood. These spheres flattened on the bottom rather quickly due to low rigidity of C-4. The dynamite selected for shot #14 was more difficult to form into a sphere, and a ribbed styrofoam structure was used to hold a plastic bag containing the charge. Each of these charges was located at the center of the test vessel by means of a flimsy plywood table that was combusted by the subsequent explosion.

Ultrasonic Thickness Measurements

Figure 3 summarizes the thickness measurements on the first vessel, using an ultrasonic pulse technique. The equipment used was a Sperry Reflectoscope UM721, a plug-in pulser-receiver unit, and a 2.25 MHZ Aerotech UT probe with a 1-inch diameter head. Light oil was used for surface coupling. The calibration was established by comparing micrometer and ultrasonic measurements on a test specimen cut from the cap of the vessel that was removed in order to install the door reinforcing ring. A precision of 0.01 inch was obtained. The measurements were taken in a pattern identical with the layout of the fiducial marks. The variation of the thicknesses with location confirms a previous experience with hot-pressed hemispheres.(3) Note that the shell is thinnest near the pole and is thickest near the main equatorial weld. The thicknesses range from 1.29 inches to 1.52 inches. By proper weighting of the data, we estimate that the average thickness of the first vessel was 1.40 inches. These results are useful for predicting the elastic-plastic response of the vessel to explosive testing and in selecting specifications for future procurement of explosion containment vessels.

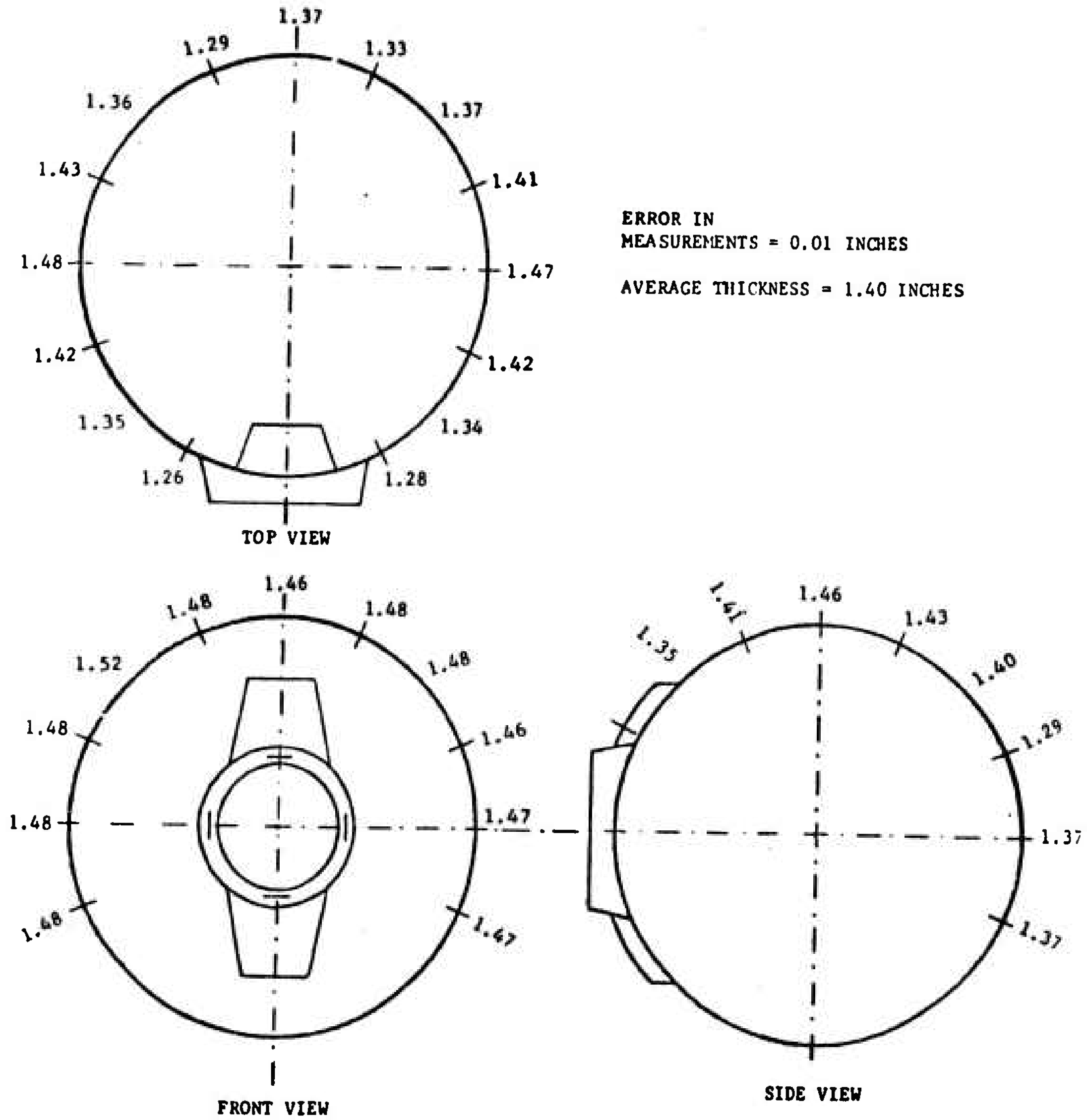


FIGURE 3 . ULTRASONIC THICKNESS MEASUREMENTS IN INCHES ON THE FIRST FIVE-FOOT EXPLOSION CONTAINMENT VESSEL

Explosive Testing of the First Vessel

Table 1 presents a summary of the explosive testing conducted on the first 5-ft diameter explosive containment vessel. Shot numbers 1 and 2 employed a 10-lb charge, and the vessel response was elastic. Shot number 3 used 20 lbs of explosive, and the result was on the threshold of plastic response. Shot numbers 4 and 5 used 25 and 30 lbs of C-4, respectively, and a small plastic response was obtained. The doors of the vessel were not closed for shot number 5. The vessel was slightly damaged when the door bolts sheared off, and the vessel recoiled against the wall of the test chamber. Using TV and movie cameras furnished by Mr. L. Wolfson, it was observed that the vent flame for shot numbers 3 and 4 was extensive and that a further reduction of the small vent area around the door ($\sim$0.25 in.^{2}) was desirable.

Repair of the damage to the first 5-ft explosion containment vessel was completed within two weeks after its occurrence. Shop work was done to the hinges, doors, and feet to repair the damage, improve the door closure, and decrease the vent area. Restoration of the strain gage wires was also accomplished. Before transporting the vessel to the Battelle West Jefferson facility, ultrasonic thickness measurements were performed. The results indicate thicknesses ranging from 1.26 inch near the pole to 1.52 inch near the main equatorial weld.

During the week of March 17, 1975, the explosive testing program for the first 5-ft vessel was resumed with Mr. Lennard Wolfson and Lt. H. D. Nix present as technical observers. As summarized in Table 1, eight additional shots were fired with no significant damage to the vessel. Shot No. 6 was 20 pounds of C-4 to check out the instrumentation and to find out if the dent at the pole or the restoration of the door hinges represented defects that precluded testing with larger charges. The effects of shot No. 6 were minimal, and it was decided that the vessel would be tested with 35 pounds of explosive. Shot No. 7 employed 35 pounds of C-4, and the vessel responded quite satisfactorily. The only damage of significance was a small bending of the support plate that connects the two hinges. This bending was probably due to blast effects. It progressed slowly throughout the test

TABLE 1. EXPLOSIVE TESTING RECORD FOR THE FIRST 5-FT DIAMETER EXPLOSIVE CONTAINMENT VESSEL

Shot Number	Test Date	Type Explosive	Explosive Weight	Technical Observers	Comments
1	2/24/75	C-4	10 lbs	None	Elastic response Minor instrumentation problems
2	2/24/75	C-4	10 lbs	None	Elastic response Instrumentation OK
3	2/25/75	C-4	20 lbs	L. Wolfson Lt. H. D. Nix	Threshold plastic response 50 seconds of venting Lost metal strip on door
4	2/25/75	C-4	25 lbs	L. Wolfson Lt. H. D. Nix	Small plastic response 50 seconds of venting Improved scope trigger
5	2/26/75	C-4	30 lbs	L. Wolfson Lt. H. D. Nix	Small plastic response Doors not closed Door bolts sheared off Door hinges damaged Dent on vessel pole Support feet twisted
6	3/17/75	C-4	20 lbs	L. Wolfson Lt. H. D. Nix	60 seconds of venting Threshold plastic response Lost eyebolt on right door
7	3/17/75	C-4	35 lbs	L. Wolfson Lt. H. D. Nix	135 seconds of venting Hinge support bent slightly First small hinge crack
8	3/18/75	C-4	35 lbs	L. Wolfson Lt. H. D. Nix	150 seconds of venting
9	3/18/75	C-4	35 lbs	L. Wolfson Lt. H. D. Nix	180 seconds of venting
10	3/18/75	C-4	35 lbs	L. Wolfson Lt. H. D. Nix	200 seconds of venting
11	3/19/75	C-4	35 lbs	L. Wolfson Lt. H. D. Nix	175 seconds of venting Lost eyebolt on left door
12	3/19/75	C-4	35 lbs	L. Wolfson Lt. H. D. Nix	150 seconds of venting Dent at pole was gone
13	3/19/75	C-4	35 lbs	L. Wolfson	135 seconds of venting Test standard met Observed det. prod. pres. hist.
14	3/20/75	60% special gelatin dynamite	47.5 lbs	L. Wolfson	25 seconds of venting Black smoke, no flames Temperature rise of 105° F Cumulative strain was only 1%

General comments:

(1) Truncated cubical charges were used for shots 1-5; approximately spherical charges were used for shots 6-14
(2) Instrumentation survived entire shot series (6-14)
(3) Small plastic response with shots 7-14
(4) Shots 7-14 gave an average incremental residual strain of 0.12%
(5) Vessel temperature rise for shots 7-13 was 90-100° F
(6) Hinge support problem progressed slowly after shot 7
(7) Small hinge cracks appeared and slowly developed after shot 7
(8) Dent at pole disappeared slowly
(9) Ring deformation was insignificant
(10) Door closure required attention after each shot

series, and led finally to three small hinge cracks. The immediate import of this damage was a slight interference with the door closure. Adjustments were made with the hinge bolts before each shot in order to minimize the vent area.

A total of seven shots of 35 pounds of C-4 were fired. Each shot caused the vessel to rise 90-100 °F in temperature, representing the absorption of 75 percent of the explosive energy. The average strain over all fiducial marks showed a slight increase in strain per shot for the first two 35-lb shots (0.103, 0.140 percent) then gradually decreasing to 0.045 percent on the last 35-lb shot. The cumulative strain of the vessel was approximately 1 percent. The reinforcing ring showed very little response (0.3 percent). It is not known if the dent at the pole had weakened that section of the vessel. The principal effect of the testing was to restore the dent region to its original spherical shape.

As a method for gaining further insight into the venting problem, it was decided after shot No. 13 that 47.5 pounds of Dupont 60 percent strength special gelatin dynamite would be fired in the vessel. The venting from shot No. 14 lasted only 25 seconds, and the test chamber filled with black smoke. The dynamic strain gage records indicated a peak strain comparable with 35 pounds of C-4, however, the resulting increase in cumulative strain was smaller than for 35 pounds of C-4.

Measurements on the First Containment Vessel

Table 2 gives the cumulative residual strain readings from the six strain gages mounted on the first five-foot vessel. The location of these gages is given in Figure 1. Dirty switch contacts rendered the results for gage numbers 1-4 invalid for shot no. 1. The contacts were polished, the gage bridges were rezeroed, and no new contact problems occurred. After each explosive test, the strain gages were read 3-4 times. A negative drift of approximately 100 microstrain was observed as the vessel cooled down to the ambient temperature in agreement with published temperature compensation data for the gages used. The results in Table 2 are for a cold vessel.

TABLE 2. CUMULATIVE RESIDUAL STRAIN READINGS FROM STRAIN GAGES AFTER SHOT #1 ON THE FIRST FIVE-FOOT EXPLOSION CONTAINMENT VESSEL

Shot Number	Amount of C-4, lbs	Gage #1, με	Gage #2, με	Gage #3, με	Gage #4, με	Gage #5, με	Gage #6, με
1(a)	10	--	--	--	--	19	23
2	10	82	9	4	19	44	22
3	20	292	7072	6100	-69	0 ± 4	0 ± 4
4	25	729	9228	14681	-121	-141	-76
5(b)	30	--	--	--	--	--	2620
5(c)	--	-512	9444	-4128	-227	6719	2662
6	20	-644	9432	460	-154	6668	2745
7	35	122	9084	3374	-222	6608	3886
8	35	-60	8962	5290	-52	6825	5399
9	35	419	8641	5958	72	7041	5866
10	35	1064	8579	7242	360	8138	7402
11	35	1679	8426	8208	445	8781	8476
12	35	2703	8399	9272	584	9261	9476
13	35	3553	8350	10002	680	9897	10512
14	47.5(d)	3977	8428	11700	1072	10298	12266

(a) The readings on gages 1-4 for Shot #1 were invalid. All gages were rezeroed prior to Shot #2.
(b) The vessel motion during Shot #5 tore away the cables on gages 1-5.
(c) Readings prior to Shot #6 after reinstallation of gage cables.
(d) Explosive was 60% strength DuPont special gelatin dynamite.

Note: Readings given here are for a cold vessel.

The results indicate that the average residual strain in the vessel shell due to the 14 explosive tests was approximately 1 per cent. The residual hoop strain (Gage #4) in the door reinforcing ring was only 0.1 percent.

Tables 3 and 4 present the results of the fiducial mark readings on the first five-foot vessel. The direct readings are summarized in Table 3, and the accumulated strains are listed in Table 4. The location of the fiducial marks is given in Figure 2. Marks 1-19 were located on the shell outer surface. A specialized tool with a curved section was used to obtain readings related to the distance between points approximately 24 inches apart. Marks 20-21 on the cradle surface were measured to verify the absence of problems with this tool. The very small variation of the readings for Marks 20-21 supports the estimate of a precision of 0.005 in. Marks 22-25 permitted a measurement of changes in the mean horizontal and vertical diameters of the reinforcing ring. After Shot #7, Mr. Wolfson suggested that a measurement of the vessel circumference near the main equatorial weld would complement the fiducial mark readings. A 50-foot steel tape was used for the circumference measurements.

As indicated in the rightmost column of Tables 3 and 4, the accumulated strain of the vessel shell after Shot #14 ranged from 0.61 to 1.45 percent. The average residual strain, as determined from the fiducial marks, was approximately 1 percent. The circumference changed by 0.82 percent during the last 7 shots. Based on the results for Marks 14-19 during the first 7 shots, the circumference probably changed by 1.11 percent during the explosive testing. Although there remain some unexplained variations in the data, the agreement among the average strain gage, fiducial, and circumference measurements is very good. The influence of the doubler plates and the cafe doors and hinges on the ring response is given by the results for Marks 22-25.

Figures 4-6 were prepared to display the results of Table 4 more clearly. Figure 4 gives the accumulated strain after Shot #14 at various

TABLE 3. ACCUMULATED STRAIN FROM FIDUCIAL MARK READINGS ON THE FIRST FIVE-FOOT EXPLOSION CONTAINMENT VESSEL

Marks[a]	After Shot #1, %	After Shot #2, %	After Shot #3, %	After Shot #4, %	After Shot #5, %	After Shot #6, %	After Shot #7, %	After Shot #8, %	After Shot #9, %	After Shot #10, %	After Shot #11, %	After Shot #12, %	After Shot #13, %	After Shot #14, %
1-2	0.01	0.04	0.01	0.01	0.32	—	0.50	0.68	0.84	1.05	1.24	1.38	1.40	1.45
2-3	—	—	—	0.30	0.32	—	0.35	0.41	0.47	0.54	0.65	0.69	0.75	0.74
3-4	—	—	—	-0.04	0.10	—	0.28	0.45	0.58	0.74	0.90	1.02	1.06	1.15
4-5	—	—	—	0.48	-0.38[b]	—	0.40[b]	0.24[b]	0.33[b]	0.43	0.57	0.68	0.76	0.84
5-6	—	—	—	0.02	0.46	—	0.65	0.78	0.88	0.96	1.09	1.21	1.28	1.29
6-7	—	—	—	0.28	0.26	—	0.33	0.38	0.47	0.54	0.67	0.72	0.76	0.73
7-8	—	—	—	0.03	0.30	—	0.44	0.59	0.80	0.92	1.12	1.16	1.21	1.19
9-10	—	—	—	0.53	0.05[b]	—	0.40[b]	0.27[b]	0.40	0.56	0.58	0.63	0.70	0.79
10-11	—	—	—	0.03	0.05	—	0.14	0.26	0.60	0.77	0.96	1.09	1.21	1.23
11-12	—	—	—	0.31	0.45	—	0.69	0.83	0.88	0.96	1.01	1.03	1.09	1.15
12-13	—	—	—	0.02	0.10	—	0.36	0.53	0.73	0.86	0.98	1.13	1.16	1.19
14-15	—	—	—	0.21	0.16	—	0.30	0.33	0.42	0.52	0.52	0.58	0.60	0.61
15-16	—	—	—	0.02	-0.03	—	0.08	0.15	0.34	0.43	0.53	0.72	0.80	0.82
16-17	—	—	—	0.25	0.50	—	0.68	0.76	0.92	0.98	1.03	1.06	1.06	1.17
17-18	—	—	—	0.00	0.00	—	0.03	0.06	0.17	0.33	0.43	0.54	0.60	0.63
18-19	—	—	—	0.20	0.28	—	0.37	0.42	0.49	0.56	0.65	0.66	0.64	0.63
20-21[c]	—	—	—	-0.07	0.00	—	-0.05	-0.05	-0.08	-0.13	-0.10	-0.07	-0.07	-0.08
22-23	0.03	0.03	0.03	0.17	0.10	—	0.09	0.10	0.13	0.04	0.09	0.13	0.03	0.12
24-25	0.03	0.04	0.06	0.10	0.00	—	-0.15	-0.19	-0.21	-0.24	-0.25	0.32	0.24	-0.31
Circum.[d]	—	—	—	—	—	—	—	0.21	0.31	0.46	0.52	0.68	0.78	0.82

(a) Refer to Table 1 for explanation
(b) Doubtful meaning due to dent at the pole
(c) Marks used for tool calibration check
(d) Calibration obtained after Shot #7

Notes: (1) The estimated error in the cumulative strain from fiducial readings is 0.03%.
(2) The estimated error in the cumulative strain from the circumference measurements is 0.01%.

TABLE 4. SUMMARY OF FIDUCIAL MARK READINGS ON THE FIRST FIVE-FOOT EXPLOSION CONTA

Marks	Initial Approximate Distance, Inches	Calibration, Inches	Relative Distance from Specialized Tools: After Shot #1, Inches	After Shot #2, Inches	After Shot #3, Inches	After Shot #4, Inches	After Shot #5, Inches	After Shot #6, Inches	After Shot #7, Inches
1-2	22	5.917	5.920	5.925	5.920	5.918	5.987	--	6.016
2-3	24	7.913	--	--	--	7.984	7.990	--	7.998
3-4	25	8.915	--	--	--	8.905	8.941	--	8.986
4-5	24	8.115	--	--	--	8.239	8.025[b,c]	--	8.212
5-6	25	8.918	--	--	--	8.924	9.034	--	9.081
6-7	24	7.936	--	--	--	8.002	7.998	--	8.016
7-8	22	5.903	--	--	--	5.909	5.967	--	5.999
9-10	24	7.954	--	--	--	8.081	7.966[b,d]	--	8.049
10-11	25	8.976	--	--	--	8.984	8.988	--	9.011
11-12	24	7.878	--	--	--	7.953	7.985	--	8.044
12-13	23	6.673	--	--	--	6.677	6.696	--	6.757
14-15	24	7.918	--	--	--	7.969	7.956	--	7.989
15-16	24	7.918	--	--	--	7.922	7.910	--	7.936
16-17	24	7.895[a]	--	--	--	7.956	8.014	--	8.059
17-18	23	6.944	--	--	--	6.945	6.945	--	6.952
18-19	24	7.894	--	--	--	7.941	7.960	--	7.982
20-21	24	7.660	--	--	--	7.655	7.660	--	7.656
22-23	20	9.004	9.009	9.009	9.009	9.038	9.023	--	9.022
24-25	20	8.998	9.003	9.005	9.009	9.018	8.998	--	8.969
Circum.[e]	197	--	--	--	--	--	--	--	5.344

(a) Readjustment from 7.995.
(b) Measurement effected by dent at pole.
(c) Reading was 8.075 by alternate method
(d) Reading was 7.975 by alternate method
(e) Add 16 feet to all circumference readings.

Notes: (1) Marks 20-21 form a standard marke
(2) Marks 22-23 form a horizontal meas
(3) Marks 24-25 form a vertical measu
(4) Circumference measured 1/2 inch f
(5) The estimated error in the fiduci
(6) The estimated error in the circum

ST FIVE-FOOT EXPLOSION CONTAINMENT VESSEL

ecialized Tools

After Shot #5, Inches	After Shot #6, Inches	After Shot #7, Inches	After Shot #8, Inches	After Shot #9, Inches	After Shot #10, Inches	After Shot #11, Inches	After Shot #12, Inches	After Shot #13, Inches	After Shot #14, Inches	Accumulated Strain, Percent
5.987	--	6.016	6.067	6.101	6.149	6.189	6.221	6.224	6.237	1.45
7.990	--	7.998	8.011	8.025	8.043	8.070	8.079	8.092	8.090	0.74
8.941	--	8.986	9.028	9.059	9.100	9.141	9.169	9.179	9.203	1.15
8.025[b,c]	--	8.212	8.172	8.194	8.219	8.251	8.278	8.298	8.316	0.84
9.034	--	9.081	9.113	9.138	9.157	9.191	9.220	9.238	9.240	1.29
7.998	--	8.016	8.027	8.049	8.066	8.097	8.109	8.119	8.112	0.73
5.967	--	5.999	6.032	6.078	6.105	6.150	6.155	6.170	6.164	1.19
7.966[b,d]	--	8.049	8.019	8.050	8.089	8.094	8.104	8.121	8.143	0.79
8.988	--	9.011	9.040	9.127	9.168	9.216	9.249	9.278	9.283	1.23
7.985	--	8.044	8.076	8.090	8.109	8.121	8.126	8.140	8.155	1.15
6.696	--	6.757	6.796	6.840	6.870	6.899	6.932	6.939	6.946	1.19
7.956	--	7.989	7.997	8.019	8.043	8.042	8.058	8.062	8.064	0.61
7.910	--	7.936	7.955	7.999	8.021	8.045	8.090	8.109	8.115	0.82
8.014	--	8.059	8.078	8.115	8.131	8.143	8.150	8.150	8.175	1.17
6.945	--	6.952	6.959	6.984	7.019	7.042	7.069	7.083	7.088	0.63
7.960	--	7.982	7.995	8.012	8.028	8.050	8.052	8.047	8.045	0.63
7.660	--	7.656	7.656	7.654	7.650	7.652	7.655	7.655	7.654	--
9.023	--	9.022	9.024	9.030	9.011	9.021	9.030	9.009	9.027	0.12
8.998	--	8.969	8.961	8.956	8.950	8.949	8.935	8.951	8.937	-0.31
--	--	5.344	5.750	5.953	6.250	6.375	6.688	6.875	6.969	0.82

s 20-21 form a standard marked on the vessel cradle.
s 22-23 form a horizontal measurement on the ring face.
s 24-25 form a vertical measurement on the ring face.
cumference measured 1/2 inch forward of the main equatorial weld.
estimated error in the fiducial mark readings is 0.005 inches.
estimated error in the circumference measurements is 0.016 inches.

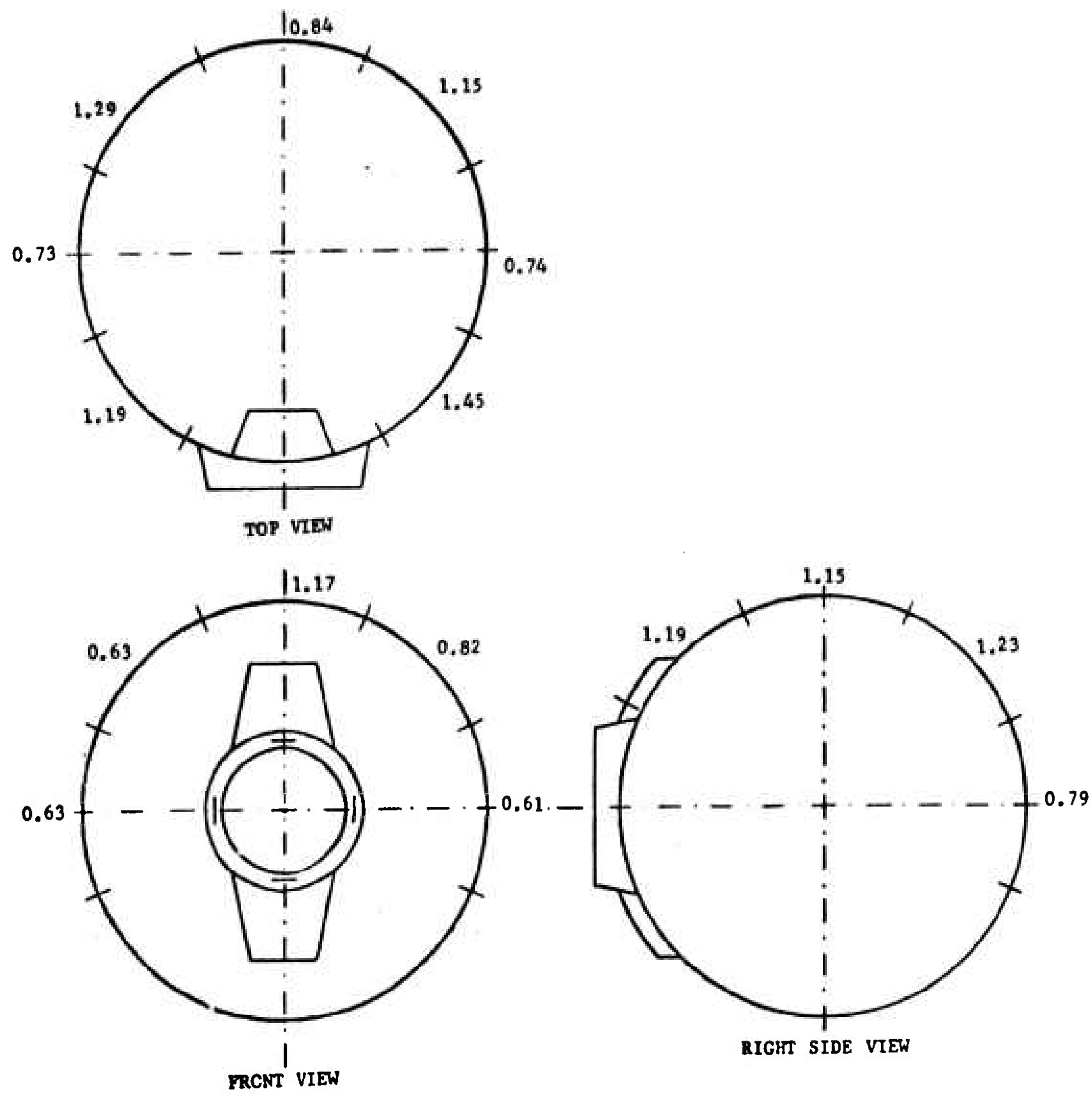


FIGURE 4. ACCUMULATED STRAIN IN PERCENT FROM FIDUCIAL MARK READINGS ON THE FIRST FIVE-FOOT EXPLOSION CONTAINMENT VESSEL AFTER SHOT #14.

positions. Figures 5 and 6 show the effect of strain hardening during the series of 35-lb shots. The average incremental strain due to Shot #7, assuming the effect of Shot #6 was negligible, was 3 times greater than that for Shot #13.

Figures 7 and 8 illustrate another interesting point. The rectangular figures at the center of each schematic sphere indicate that the charge for shot #5 was intentionally rotated 45° about its vertical axis with respect to the position of the charge for shot #4. Observe that the maximum increments in residual strain occurred opposite the major faces of the cube. The pattern rotated 45° between shot numbers 4 and 5. The data gives clear evidence of a charge shape effect, even though the corners of the cubes were removed. The results for strain gage #6, the only gage remaining intact after shot #5, in Table 2 agree with this interpretation.

Good thermocouple data were obtained from an ISA type K thermocouple spot welded near strain gage #3. Table 5 gives the results for the thermocouple measurements. The average observed temperature increase for shots 7-13 was 92.4 ± 3.6° F. The results show that the vessel was not only effective in containing the blast and fragments but retained 75 percent of the chemical energy as well. Reduction of the vent area will not only reduce the flame hazard but will cause an even greater containment of the energy. The adiabatic ΔT given in Table 5 is calcluated on the assumption that all of the explosive energy is used to heat the 5300-lb containment vessel (excluding the 1000-lb cradle). The formula used was

$$\Delta T = \Delta Q / W_v C_v$$

$$= q_e W_e / W_v C_v \quad ,$$

where ΔT is the temperature increase in °F, ΔQ is the heat absorbed by the vessel, W_v is the weight of the vessel, C_v is the specific heat of the vessel, q_e is the specific energy of the explosive, and W_e is the weight of explosive. The quantity

$$\frac{q_e}{W_v C_v} = \frac{(20.4 \times 10^6 \text{lb-in/lb})\ (0.0012854\ \text{BTU/Ft-lb})}{(5300\ \text{lb})\ (0.115\ \text{BTU/lb-°F})\ (12\ \text{in/ft})}$$

$$= 3.58\ \text{°F/lb}.$$

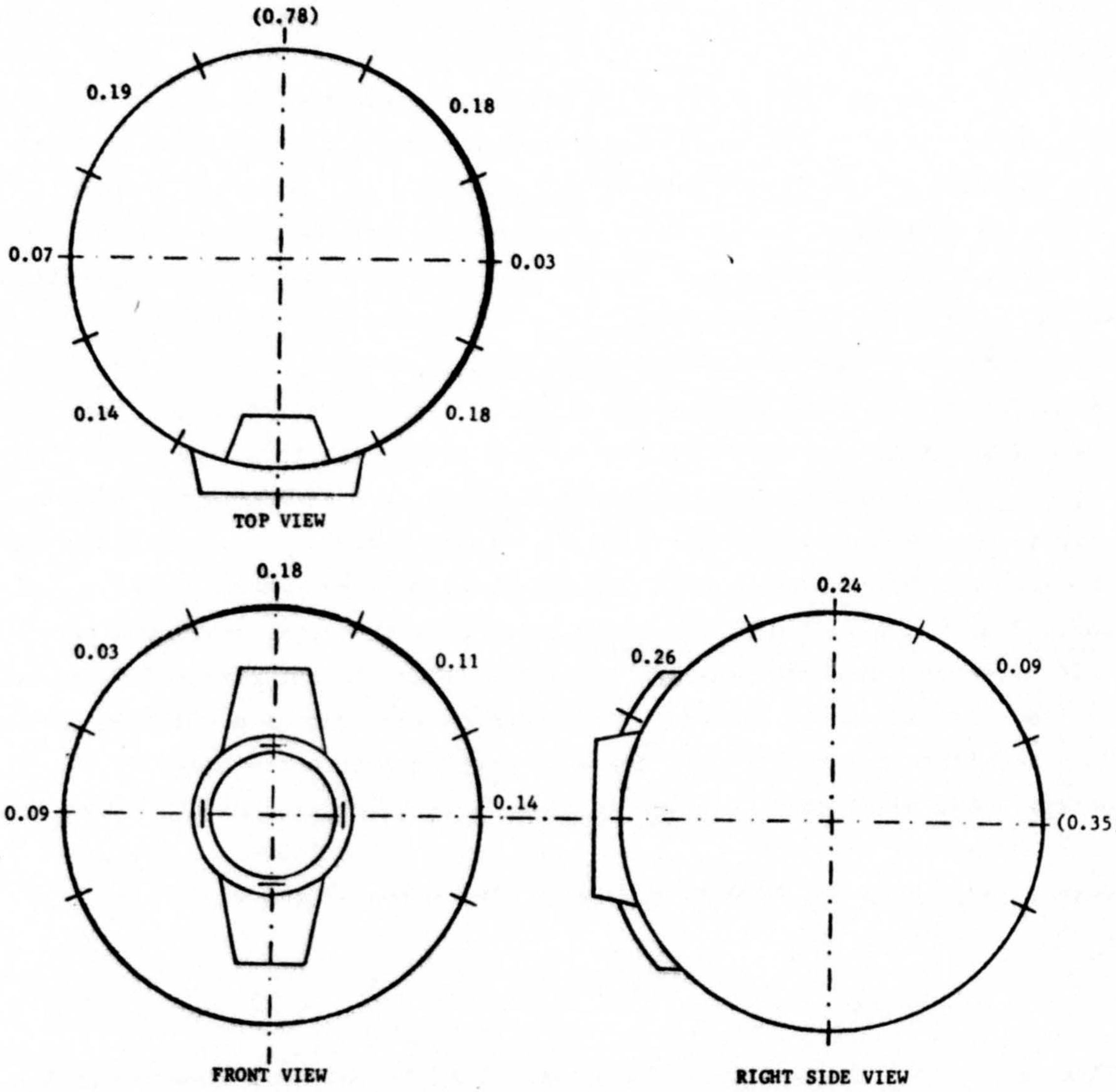


FIGURE 5. INCREMENTAL STRAIN IN PERCENT FROM FIDUCIAL MARK READINGS ON THE FIRST FIVE-FOOT EXPLOSION CONTAINMENT VESSEL DUE TO SHOTS 6 & 7.

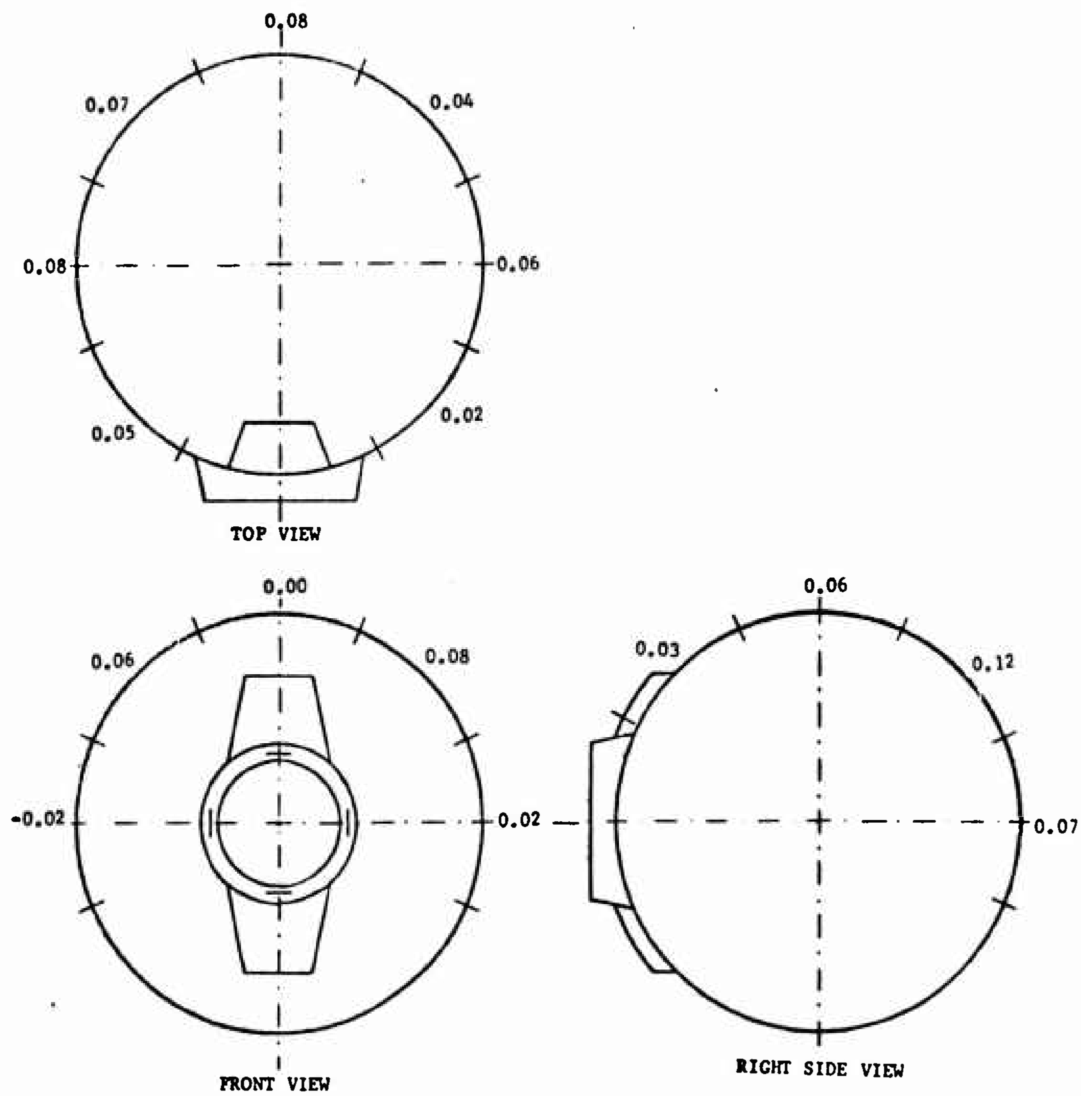


FIGURE 6. INCREMENTAL STRAIN IN PERCENT FROM FIDUCIAL MARK READINGS ON THE FIRST FIVE-FOOT EXPLOSION CONTAINMENT VESSEL DUE TO SHOT 13.

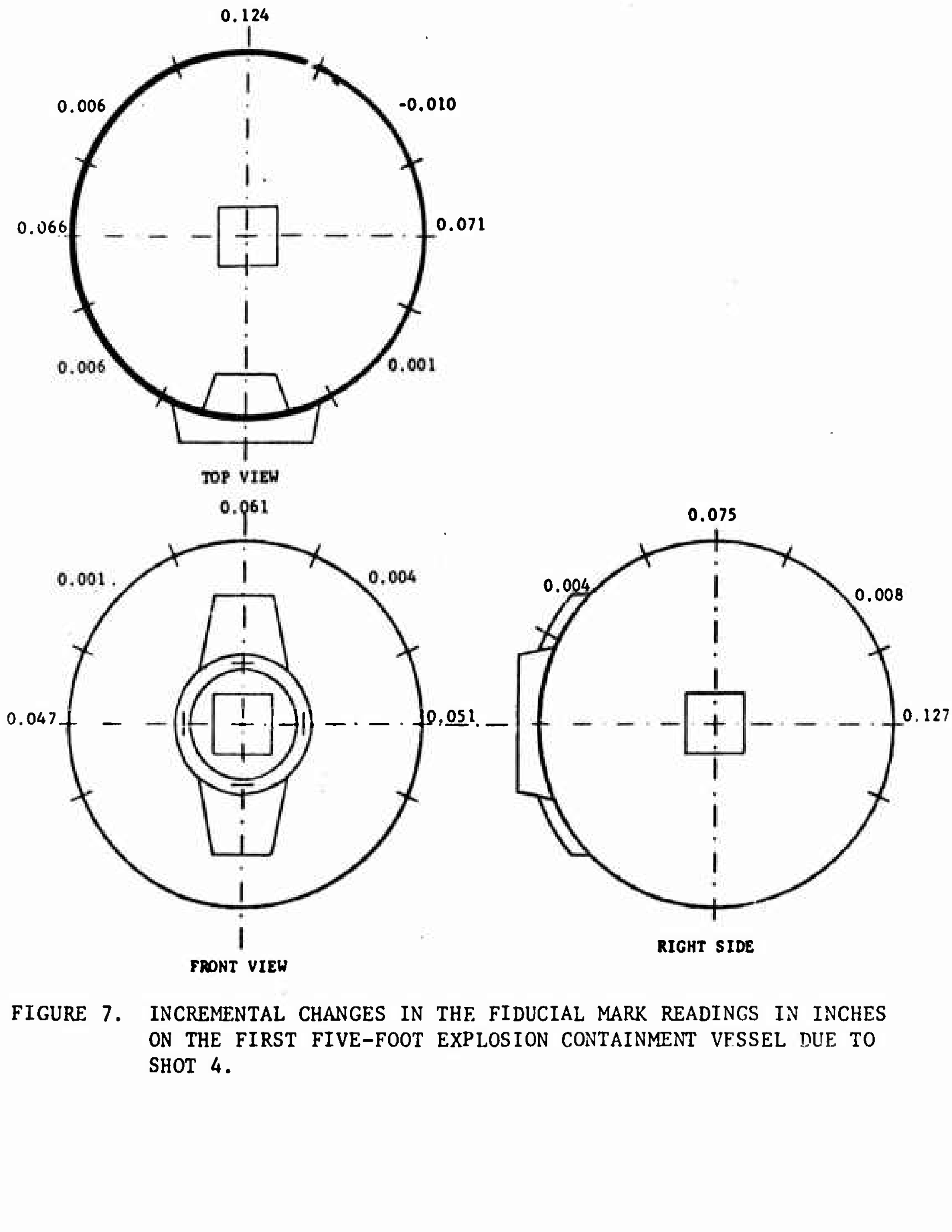


FIGURE 7. INCREMENTAL CHANGES IN THE FIDUCIAL MARK READINGS IN INCHES ON THE FIRST FIVE-FOOT EXPLOSION CONTAINMENT VESSEL DUE TO SHOT 4.

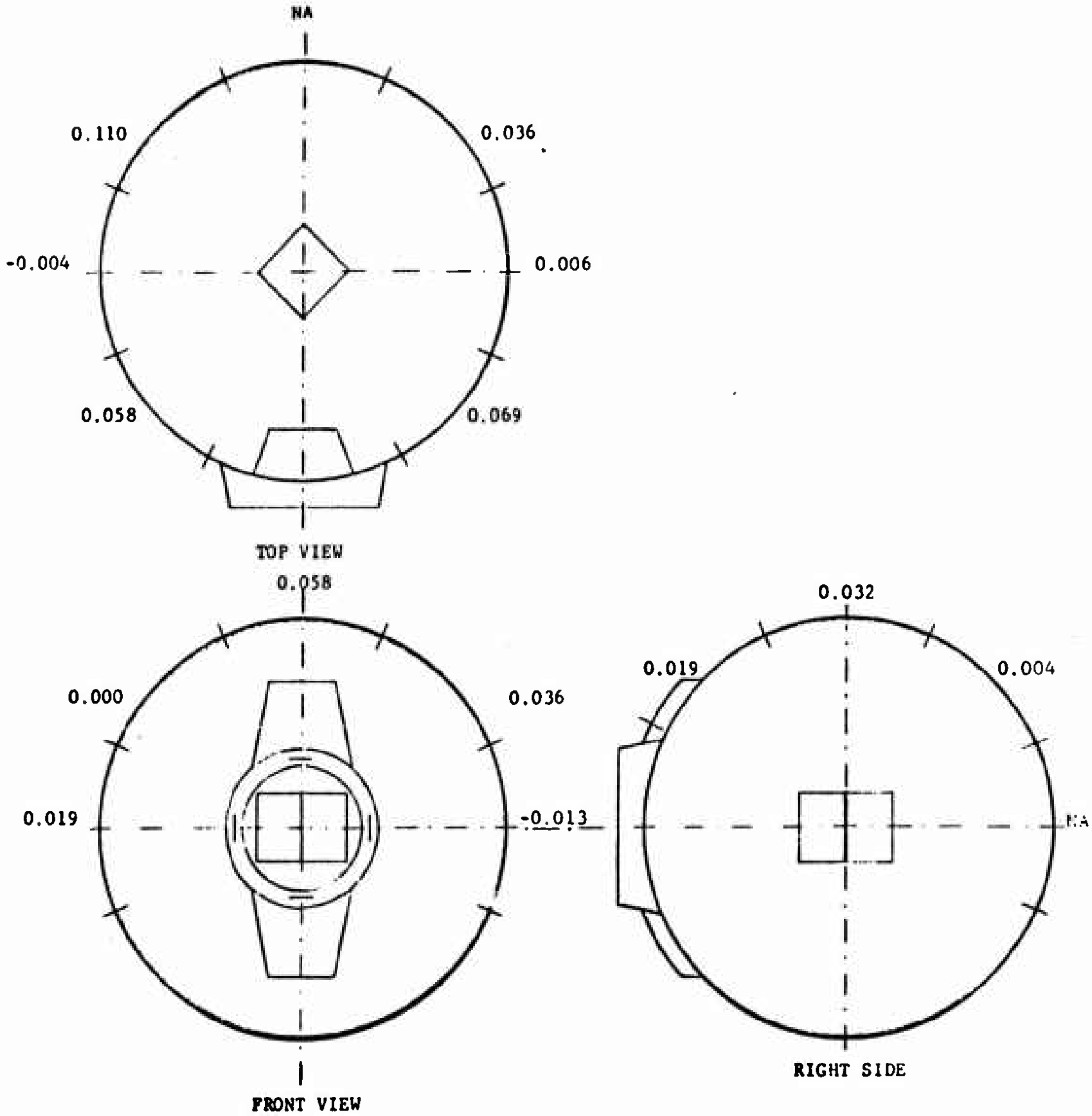


FIGURE 8. INCREMENTAL CHANGES IN THE FIDUCIAL MARK READINGS IN INCHES ON THE FIRST FIVE-FOOT EXPLOSION CONTAINMENT VESSEL DUE TO SHOT 5.

TABLE 5. SUMMARY OF THERMOCOUPLE MEASUREMENTS OF THE FIRST FIVE-FOOT EXPLOSION CONTAINMENT VESSEL

Shot Number	Amount of C-4, lbs	Initial Temperature, °F	Observed ΔT, °F	Adiabatic ΔT, °F	ΔT Ratio, %
1	10	46	28.3	35.9	79
2	10	56	28.3	35.9	79
3	20	40	46.5	71.7	65
4	25[(a)]	--	—	89.6	--
5	30[(a)]	—	—	107.6	—
6	20	41	61.3	71.7	85
7	35	76	91.3	125.5	73
8	35	42	96.8	125.5	77
9	35	72	89.6	125.5	71
10	35	79	88.8	125.5	71
11	35	55	98.0	125.5	78
12	35	67	88.3	125.5	70
13	35	57	94.3	125.5	75
14	47.5[(b)]	43	105.1	--	--

(a) Thermocouple wire separated from vessel during initial response.
(b) Explosive was 60% strength DuPont special gelatin dynamite.

Notes: (1) Chromel-Alumel thermocouple used
(2) Adiabatic ΔT is the predicted temperature increase, if all energy is used to heat vessel.
(3) The average observed ΔT for shots 7-13 was 92.4 ± 3.6°F.

where

t = vessel wall thickness

= 1.37 in. at Gage No. 3

E = Young's Modulus = 3×10^7 psi

ε = the measured strain

R = the vessel radius = 30 in.

ν = Poisson's ratio = 0.28

Evaluation of the above expression for the maximum elastic strain measured yields

$$P_{max} = 2,473 \text{ psi}$$

For 35 lb of C-4 in this 5-ft sphere the explosive per cubic foot is approximately 0.53 lb/ft^3. Evaluation of Proctor's[8] expression for the confined explosion gas pressure of a mixture of 91% RDX/9% wax as a mock-up for Composition C-4 explosive at a charge density of 0.53 lb/ft^3 yields a predicted static pressure of 1845 psi. Thus the pressure calculated from the strain gage reading is 34% higher than the predicted value. Possible partial reasons for this discrepancy are the non-uniform nature of the vessel wall thickness and the combustion of the wooden frame in the vessel used to support the charge. In any event, this was the only measurement made of this quantity and no firm conclusions should be drawn from it.

Discussion

After firing each of the first five charges, the gases venting through the open notches at the ends of the split in the doors burned with a bright noisy flame several feet in length extending from the port of the vessel as viewed by movie coverage and a closed-circuit TV camera provided by Mr. Len Wolfson of NEODF.

During the time the doors were being repaired after Shot 5, additional metal was welded on to one of the doors at both edges, and ground down to nicely fill the original wedge shaped notch at the edges of the

The quantity $Q_e = 20.4 \times 10^6$ lb-in/lb for the explosive C-4 was obtained from the book by Baker[6], and the quantity $C_v = 0.115$ BTU/lb-°F for steel was obtained from "The Handbook of Chemistry and Physics". Thus the largest possible temperature rise for the vessel was calculated for Table 5 by means of the formula

$$\Delta T = (3.58\ °F/lb)\ W_e\ .$$

The observed values of ΔT ranged from 65 to 85 percent of the predicted maximum possible ΔT. The percentage of energy containment could be increased further if venting were eliminated, for example, with a single pin door design[7].

Table 6 gives the dynamic first cycle maximum strains as recorded on oscilloscope photographic records. No readable records were obtained on the first four shots, principally due to the occurrence of late oscilloscope triggers so that the first cycle strain could not be identified with certainty. It will be recalled that the location of the strain gages on the vessel and ring are given in Figure 1. No extensive analysis of this data has been performed, however there appear to be certain inconsistencies in the results which are not understood at present.

In shot 13, the output of strain gage no. 3 was also connected to an oscilloscope sweeping at 5 sec/cm. In addition to the initial oscilloscope sweep, several additional sweeps were recorded so that the new baseline after venting of the gas pressure was recorded. This record shows a baseline shift of 766 $\mu\varepsilon$ in good agreement with the shift shown in Table 2 for gage no. 3 on Shot 13 of 730 $\mu\varepsilon$, the initial oscilloscope sweep shows an initial "static" strain after the shot of 612 $\mu\varepsilon$ referenced to the new "relaxed" baseline. The strain rose gradually in about 5 sec to a maximum of 650 $\mu\varepsilon$. Since this strain was recovered after venting the internal gas pressure, it was most likely elastic. If it was elastic then it may be related to the internal pressure in the vessel by the expression

$$P = 2tE\varepsilon/R(1-\nu)$$

TABLE 6. DYNAMIC FIRST CYCLE MAXIMUM STRAINS FIRST FIVE-FOOT EXPLOSION CONTAINMENT VESSEL

Shot Number	Gage Number 1	2	3	4
	με	με	με	με
4	1480?	3690	Off Scale	1512
5	1295	2709	2318?	1130?
6	1333	1551	Off Scale	1618
7	2882	2318	4806	1908
8	2159	2340	4076	2168
9	2636	1636	2709	2144
10	2840	2509	3440	2474
11	2795	1932	3321	2002
12	3636	2204	3407	2544
13	Bad Record	Bad Record	3298	2450
14	2872	2168	4415	2342

Note: No readable records were obtained from Shot Numbers 1-3 due to various difficulties.

doors to reduce the venting rate, and a new overlapping strap was fastened on the back of this door to cover the small gap between the doors. Venting was still severe enough to produce a noisy, hot flame at the port, though smaller than the original flame noted. For the 35-lb shots, the venting time increased from 3 min 15 sec for Shot 7 up to 3 min 20 sec for Shot 10, then decreased with each successive shot to 2 min 15 sec again at Shot 13. The 47.5-lb dynamite Shot 14 vented in 25 sec, with little or no flame at the port. Post shot examination showed that appreciable, ($\sim$1/8-in.) metal had been eroded away along the outer edges of the doors where the principal gap was already present during the escape of the detonation product gases from the dynamite. There was also a layer of grey ash inside the vessel whereas the 35-lb C-4 charge detonation had left the interior of the vessel quite clean.

At the conclusion of testing there was no evidence of cracking or failure of any of the main structural welds, or of the vessel surface or reinforcing ring of any kind. The vertical reinforcing plate used to reinforce the two hinge pivot straps had been bowed inward to contact the doors and caused minor difficulty in opening and closing the doors. The bowing of these plates also pulled the inner ends of the hinge pivot straps slightly closer together, initiating small cracks in welds at the outside corners of three of the four hinge pivot straps where they were welded to the reinforcing ring. None of these had propagated far enough to produce any sort of failure however.

After shipment of the first 5-ft vessel to NEODF an exaggerated swelling on the bottom surface of the vessel was noted which is not visible with the vessel on its cradle. As shown by tests on the second vessel, the bottom swelling was apparently caused by the additional momentum transferred to the bottom of the vessel by the 1/4-in. plywood top on the wooden stand used to support the charge. Directly opposite the bottom of the vessel, on the extreme top of the vessel, a somewhat exaggerated strain is also apparent. This was probably caused by a momentum conservation effect.

Explosive Testing of the Second Vessel

This vessel had a port reinforcing ring of A537-72A, Cl.2 material, whereas the first vessel tested had a reinforcing ring of A-350, Cl.3 material. In this vessel as well as the trailer mounted vessels delivered the door design was altered as follows: the two doors fitted together along their entire mating surfaces with a change in the angle of the mating surfaces about halfway through the door thickness. The strap covering the split from the inside was made heavier and bolted on with hanger bolts. Special, spring-loaded blocks overlapping the joint between the doors to affect a better seal at the top and bottom were also installed. The hinge support plate which was bent during the first tests was modified to reduce the blast loading on it and provide the maximum possible clearance between it and the door.

When prepared for testing, the second vessel cradle was supported on railroad ties along both sides of the cradle to allow access to the bottom of the vessel for observation and measurements. The modified set of fiducial marks used on this vessel are shown in Figure 9. No strain gages were attached to this vessel.

Three 35-lb spherical charges of Composition C-4 were fired in this vessel. As before, the charges were made up by packing the C-4 into a spherical mold to a density near 1.55 g/cm^3.

Table 7 gives a summary of the fiducial mark readings taken on this vessel. The measurements were made using the same specialized tool used for the first vessel. Table 8 gives the strains calculated from the changes in fiducial gage lengths for this shot sequence.

The charge for Shot 1 was supported on the same design stand used in testing the first vessel, i.e. a 10-in.-square, 1/4-in. plywood top supported on 24-in., 1 x 2 legs. The distribution of strains from this shot is shown in Figure 10. Note the relatively larger strain produced on the bottom of the vessel than at other locations.

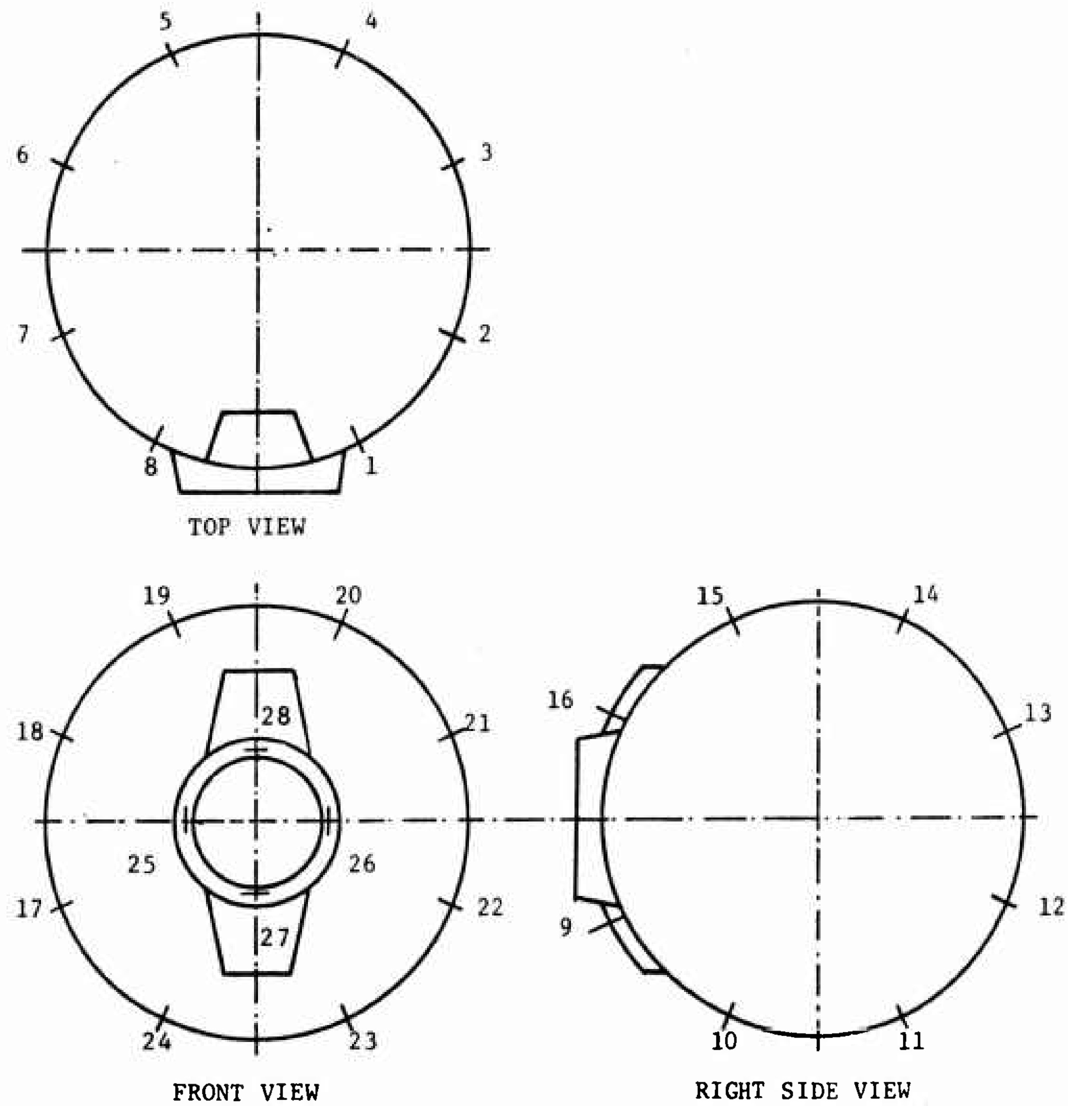


FIGURE 9. LOCATION OF FIDUCIAL MARKS ON SECOND 5-FT DIAMETER EXPLOSION CONTAINMENT VESSEL

TABLE 7 . SUMMARY OF FIDUCIAL MARK READINGS ON SECOND FIVE-FOOT EXPLOSION CONTAINMENT VESSEL

Marks	Approximate Initial Distance Inches	Relative Distance from Specialized Tools: Calibration Inches	After Shot 1 Inches	After Shot 2 Inches	After Shot 3 Inches
1-2	22	5.900	5.958	6.040	6.100
2-3	24	7.896	7.895	7.900	7.903
3-4	25	8.812	8.853	8.905	8.975
4-5	24	8.095	8.085	8.097	8.126
5-6	25	9.010	9.051	0.112	9.150
6-7	24	7.995	7.994	8.000	8.008
7-8	21	5.000	5.051	5.115	5.161
9-10	23	6.645	6.715	6.813	6.916
10-11	24	8.068	8.248	8.295	8.372
11-12	25	8.901	8.954	9.035	9.133
12-13	24	8.016	8.003	8.028	8.061
13-14	25	8.952	8.970	9.007	9.075
14-15	24	7.812	7.911	7.973	8.076
15-16	23	6.920	6.960	7.020	7.073
17-18	24	8.154	8.155	8.150	8.180
18-19	25	8.930	8.944	8.957	8.962
19-20	24	8.221	8.311	8.333	8.497
20-21	25	9.085	9.092	9.089	9.130
21-22	24	7.990	7.005	7.000	8.003
22-23	25	9.013	9.040	9.104	9.175
23-24	24	7.645	7.885	7.927	7.975
24-17	25	9.020	9.047	9.100	9.170
25-26	20	8.817	8.820	8.815	8.811
27-28	20	9.005	8.985	8.966	8.967

TABLE 8 . CALCULATED STRAIN FROM FIDUCIAL MARK READINGS ON THE SECOND FIVE-FOOT EXPLOSION CONTAINMENT VESSEL

	After Shot 1	After Shot 2		After Shot 3	
		Individual	Cumulative	Individual	Cumulative
Marks	%	%	%	%	%
1-2	.26	.37	.64	.27	.91
2-3	-.004	.02	.02	.01	.03
3-4	.17	.21	.37	.28	.66
4-5	-.04	.05	.01	.11	.12
5-6	.16	.20	.37	.15	.52
6-7	-.004	.03	.02	.03	.05
7-8	.24	.26	.50	.22	.72
9-10	.31	.43	.74	.45	1.20
10-11	.75	.20	.94	.32	1.26
11-12	.21	.33	.54	.39	.93
12-13	-.05	.10	.05	.14	.19
13-14	.07	.15	.22	.27	.49
14-15	.42	.26	.68	.43	1.11
15-16	.17	.26	.44	.23	.67
17-18	.004	-.02	-.02	.12	.11
18-19	.06	.05	.11	.0	.13
19-20	.37	.09	.46	.68	1.14
20-21	.03	-.01	.02	.16	.18
21-22	.02	.02	.04	.02	.05
22-23	.11	.26	.36	.28	.65
23-24	1.02	.18	1.19	.20	1.40
24-17	.11	.21	.32	.09	.41
25-26	.02	-.03	-.01	-.02	-.03
27-28	-.10	-.09	-.19	.005	-.19

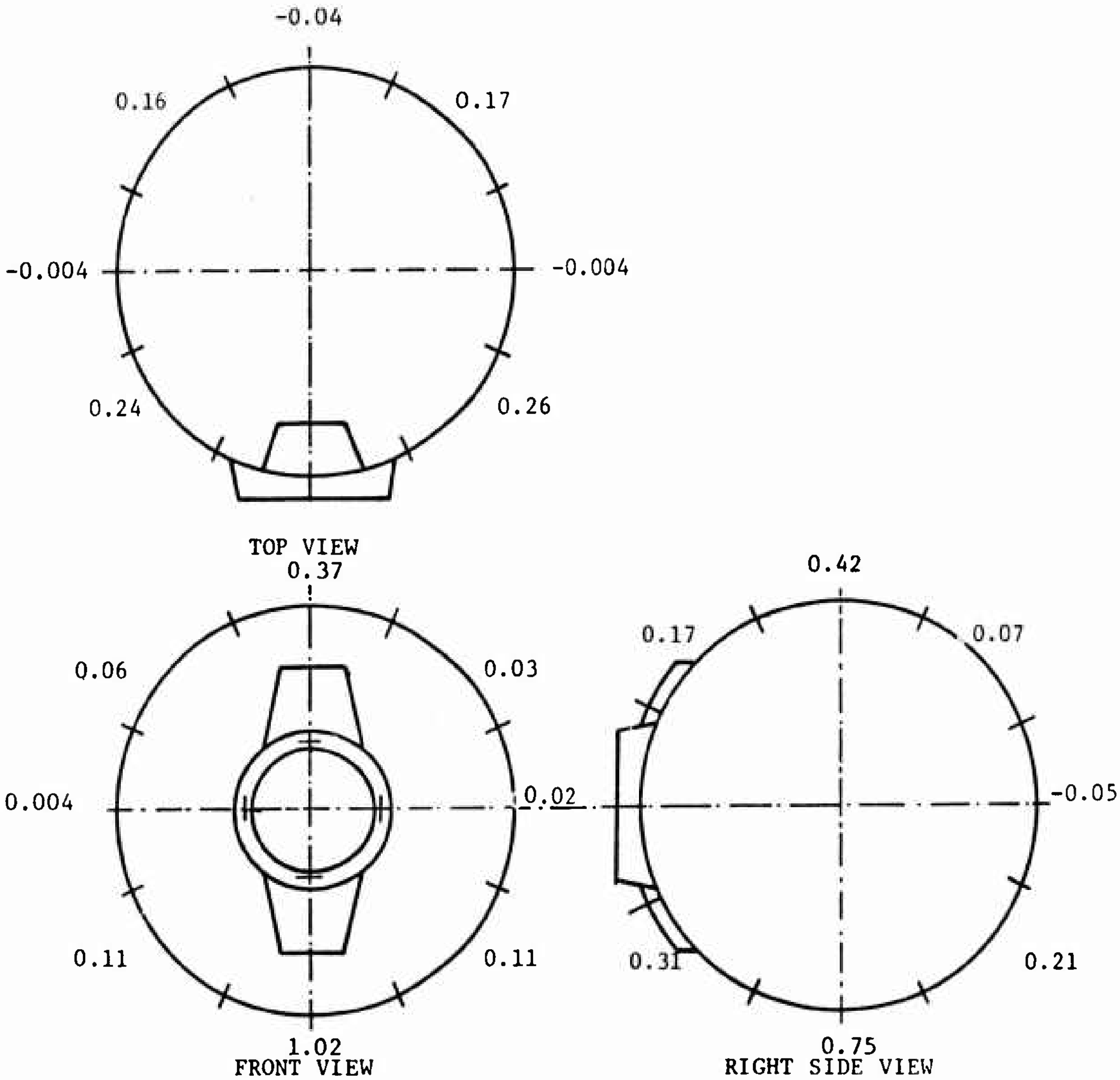


FIGURE 10. INCREMENTAL STRAINS IN PERCENT FROM FIDUCIAL MARK READINGS FOR SHOT 1 IN THE SECOND 5-FT DIAMETER BLAST CONTAINMENT CHAMBER.

As a check whether the plywood top on the charge support stand was responsible for this observation, all but a narrow strip was cut away from the top of the similar stand prepared for Shot 2. To maintain the charge in the vessel center without direct support under the bottom, 1 x 2-in. strips of Styrofoam were taped to the remaining edges of the stand top. The strain distribution resulting from this shot is shown in Figure 11. It will be noted that the exaggerated strains at both the bottom and top of the vessel were eliminated by this modification in the charge support.

A similar open-topped support stand was used for Shot 3 with similar results.

The modifications to the doors to affect a better seal were fairly effective. The escaping detonation product gas did not ignite after the first shot and venting of the gases continued for about 13 minutes after the shot. After Shot 2, the escaping gases ignited and burned at the port for about 10 minutes after the shot with flames about 3 ft in length. After the third shot, the gases burned for 6 sec then went out. Venting continued for a total of less than 10 minutes after the shot.

Free air blast pressure measurements were made directly in front of the vessel port at distances of 5-1/2 and 13-1/2-ft for all three shots using ST-7A side-on blast pressure transducers provided by Mr. Wolfson of NEODF. The peak side-on pressures at 5-1/2-ft were 3.42, 2.97, and 1.61 psi for Shot nos. 1-3 respectively. In each case the maximum pressure was the second shock observed, following the first by 0.2-0.4 msec. The peak side-on pressures at 13-1/2-ft were 0.95, 0.92, and 0.53 psi for the three shots respectively. In Shot 1 the first two shocks had coalesced at 13-1/2 ft, while the second shock was still present and the largest in the latter two shots. In each case, three successive shocks were clearly resolved at the closer distance with the third shock of smaller amplitude. The positive duration of the three-shock group was 1.1 msec in each of the three shots.

After the third shot the vessel remained in excellent condition with the only apparent evidence being a slight opening of a gap between the two doors as expected due to the strain of the vessel. The average strain of

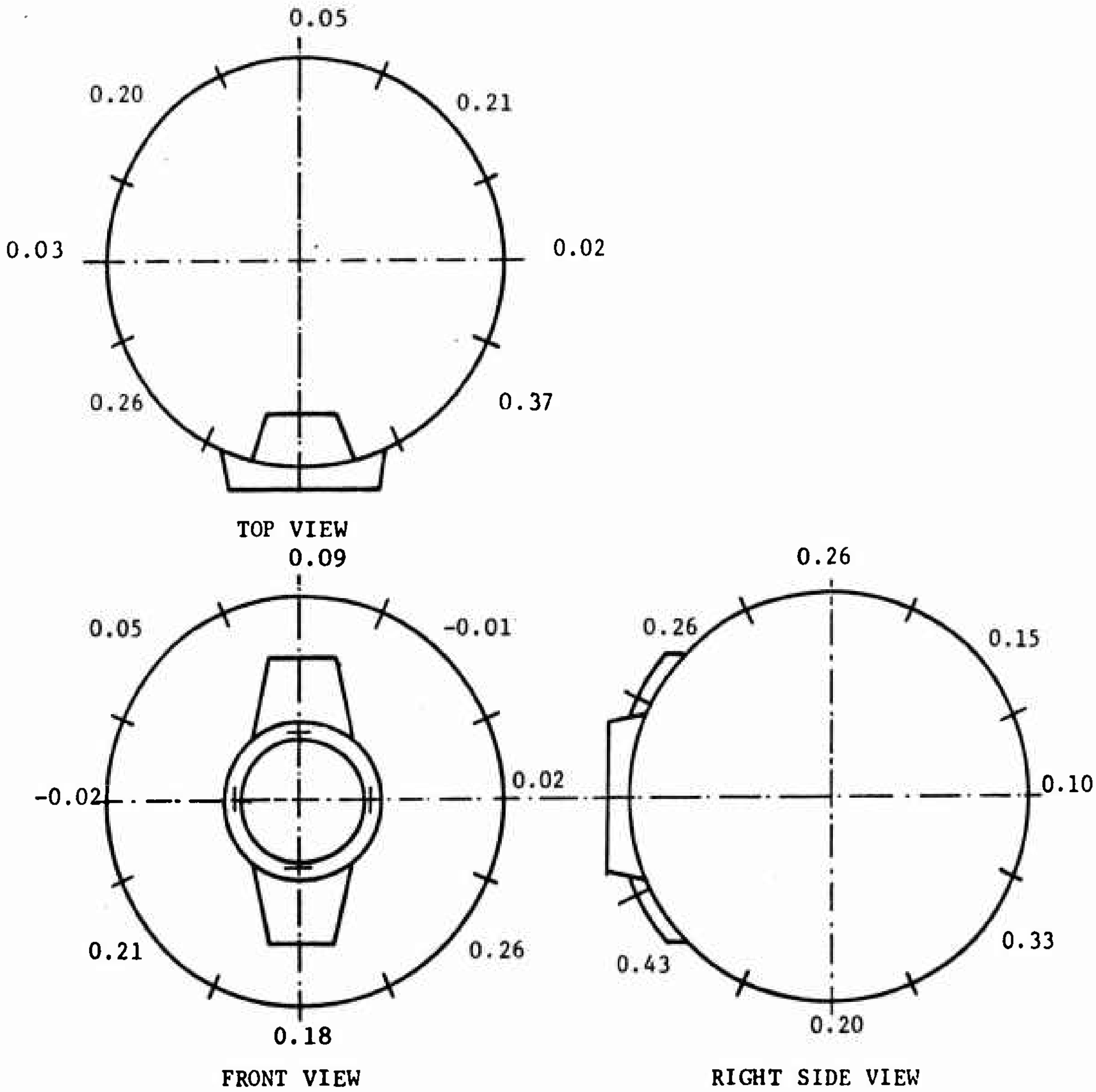


FIGURE 11. INCREMENTAL STRAINS IN PERCENT FROM FIDUCIAL MARK READINGS FOR SHOT 2 IN THE SECOND 5-FT DIAMETER BLAST CONTAINMENT CHAMBER

0.6 percent could only be detected by detailed measurements of the fiducial gage lengths, not by outward appearance. The slight reduction in the vertical and horizontal distances across the reinforcing ring noted in Table 8 for marks 25-26, and 27-28 was probably caused by a slight inward rotational deformation of reinforcing ring. Although the ring for this vessel was of a different material than that used in the first vessel, both were machined according to the same drawing. The ring on the first vessel had suffered a slight outward rotational deformation of the ring. There was no evidence of any lateral bending of either ring associated with the split in the doors.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. The concept of complete blast containment was proven in the vessel design developed in this program for 35-lb charges of C-4.
2. The plastic strain increments per 35-lb shot were small, 0.14 to 0.045 percent. In smaller vessels, single shot plastic strain increments up to 3.8 percent have been successfully contained(3). Thus it seems highly probable that considerably larger charges could be contained for a limited number of shots in vessels of the size built during this program. A spherical charge in the range of 70-80 lb of C-4 is predicted to produce only 1 percent plastic strain, which should still be a safe situation.
3. Where limited numbers of detonations are to be contained, 40% or more savings in containment vessel weight can be realized by designing for plastic deformation of the containment vessel.
4. In a containment vessel designed for plastic deformation, the occurrence of small, 1-1 1/2 percent strains has been proven not to impair the vessel's blast containment capability for blasts which will produce small additional plastic strain increments.

Recommendations

1. The maximum charge containment capability of the vessels fabricated in this program has not been proven. It is recommended that this be determined for one or more of the prototypes fabricated during this program to determine and demonstrate the margin of safety present in their design.
2. The large, multiply repeated strain cycles which blast containment vessel experiences, at least locally, for charges just below the elastic limit suggest extreme care should be exercised in the use of a vessel for large numbers of repeated firings to insure that fatigue failures are not induced.

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(3) B. D. Trott, J. E. Backofen, Jr., and J. J. White, III, "Design of Explosion Blast Containment Vessels for Explosive Ordnance Disposal Units", Final Report on Contract No. DAAA21-72-C-0129 to Picatinny Arsenal, Battelle Columbus Laboratories, June, 1975.

(4) Roark, R. J., "Formulas for Stress and Strain", McGraw-Hill, New York, 4th Edition, 1965, p. 225, Case 36.

(5) Ibid., p. 228, Case 50.

(6) W. E. Baker, J. Appl. Mech., 27, 139 (1960)

(7) Reference 3 above, p. 16.

(8) J. F. Proctor, "Internal Blast Damage Mechanisms Computer Program," NOLTR 72-231, Naval Ordnance Laboratory, White, Oak, Silver Spring, Maryland, 31 August 1972.

APPENDIX A

OUTPUT FROM COMPUTER PROGRAM SPLAS

VESSEL DIAMETER = 5.00 FEET. WALL THICKNESS = 1.290 INCHES

METAL PROPERTIES DENSITY = .283 LBS/CU.IN. MODULUS = .300E+08 PSI
POISSONS RATIO = .270 WORK HARDENING
YIELD STRENGTH = 80000. PSI COEFFICIENT = 100000. PSI

ATMOSPHERIC CONDITIONS PRESSURE = 14.7 PSI TEMPERATURE = 25. DEG CENTIGRADE

PENTOLITE (PETN/TNT,50/50)

WEIGHT OF CHARGE LBS	PEAK PRESSURE PSI	POSITIVE DURATION MILLISEC	PULSE LENGTH PSI	YIELD TIME MSEC	MAXIMUM DEFORMATION STRESS PSI	TIME MSEC	DEFLECTION INCH	STRAIN IN/IN	RESIDUAL DEFLECTION INCH	DEFORM STRAIN IN/IN	OXIDATION LAST PRODUCT	PERCENT	CONFINED EXPLOSION GAS PRES. PSI	EXPLOSIVE GAS STRESS PSI
1 2.000	1782.	.136	.120	********	15327.	.196	.0112	.00037	0.0000	0.00000	COMPLETE	0.0	206.	2397.
IMPULSE =	121.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6005.	DEG R
1 2.518	2122.	.137	.121	********	18373.	.196	.0134	.00045	0.0000	0.00000	COMPLETE	0.0	248.	2885.
IMPULSE =	146.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6705.	DEG R
1 3.170	2507.	.140	.124	********	21944.	.196	.0160	.00053	0.0000	0.00000	CO2	80.9	280.	3257.
IMPULSE =	175.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6791.	DEG R
1 3.991	2940.	.144	.128	********	26200.	.196	.0191	.00064	0.0000	0.00000	CO2	61.4	315.	3660.
IMPULSE =	211.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6717.	DEG R
1 5.024	3423.	.149	.133	********	31293.	.197	.0228	.00076	0.0000	0.00000	CO2	46.0	358.	4166.
IMPULSE =	255.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6644.	DEG R
1 6.325	3960.	.155	.139	********	37378.	.198	.0273	.00091	0.0000	0.00000	CO2	33.7	413.	4801.
IMPULSE =	308.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6572.	DEG R
1 7.962	4553.	.163	.146	********	44633.	.200	.0326	.00109	0.0000	0.00000	CO2	23.9	481.	5598.
IMPULSE =	372.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6503.	DEG R
1 10.024	5205.	.173	.154	********	53259.	.202	.0389	.00130	0.0000	0.00000	CO2	16.2	568.	6600.
IMPULSE =	451.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6439.	DEG R
1 12.619	5920.	.185	.164	********	63477.	.205	.0463	.00154	0.0000	0.00000	CO2	10.0	676.	7860.
IMPULSE =	548.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6380.	DEG R
1 15.887	6703.	.199	.175	********	75526.	.208	.0551	.00184	0.0000	0.00000	CO2	5.1	812.	9444.
IMPULSE =	666.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6328.	DEG R
4 20.000	7558.	.215	.187	.167	80025.	.216	.0659	.00220	.0075	.00025	CO2	1.3	984.	11437.
IMPULSE =	811.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6283.	DEG R
4 25.179	8491.	.233	.200	.145	80077.	.234	.0814	.00271	.0229	.00076	CO	98.2	1205.	14013.
IMPULSE =	989.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6331.	DEG R
4 31.698	9509.	.254	.214	.131	80152.	.262	.1041	.00347	.0456	.00152	CO	95.7	1488.	17301.
IMPULSE =	1208.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6422.	DEG R
4 39.905	10619.	.278	.230	.119	80268.	.302	.1389	.00463	.0803	.00268	CO	93.8	1844.	21437.
IMPULSE =	1479.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6498.	DEG R
4 50.238	11831.	.306	.247	.110	80452.	.360	.1940	.00647	.1352	.00451	CO	92.2	2291.	26641.
IMPULSE =	1812.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6561.	DEG R
4 63.246	13153.	.338	.265	.102	80758.	.447	.2858	.00953	.2268	.00756	CO	91.0	2854.	33190.
IMPULSE =	2225.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6613.	DEG R
4 79.621	14596.	.375	.283	.096	81309.	.588	.4510	.01503	.3917	.01306	CO	90.0	3563.	41434.
IMPULSE =	2736.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6656.	DEG R
4 100.237	16172.	.417	.302	.090	82443.	.852	.7912	.02637	.7310	.02437	CO	89.2	4456.	51810.
IMPULSE =	3370.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6690.	DEG R
4 126.191	17896.	.465	.320	.084	85484.	1.478	1.7037	.05679	1.6413	.05471	CO	88.6	5579.	64873.
IMPULSE =	4157.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6718.	DEG R

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4 158.866  19781.       .519    .336    .079   97477.  3.122  5.3014   .17671   5.2302   .17434       CO  88.1   6993.     81316.
IMPULSE =   5135. PSI-MSEC                                                       EXPLOSIVE GAS TEMPERATURE =     6741. DEG R
4 200.000  21845.       .582    .348    .075  130569.  4.571 15.2292   .50764  15.1338   .50446       CO  87.8   8773.    102816.
IMPULSE =   6354. PSI-MSEC                                                       EXPLOSIVE GAS TEMPERATURE =     6759. DEG R
4 251.785  24106.       .653    .355    .071  180150.  5.104 30.1033  1.00344  29.9718   .99986       CO  87.4  11014.    128375.
IMPULSE =   7874. PSI-MSEC                                                       EXPLOSIVE GAS TEMPERATURE =     6773. DEG R
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VESSEL DIAMETER = 5.00 FEET, WALL THICKNESS = 1.410 INCHES

METAL PROPERTIES DENSITY = .283 LBS/CU.IN. MODULUS = .300E+08 PSI
POISSONS RATIO = .270 WORK HARDENING
YIELD STRENGTH = 80000. PSI COEFFICIENT = 100000. PSI

ATMOSPHERIC CONDITIONS PRESSURE = 14.7 PSI TEMPERATURE = 25. DEG CENTIGRADE

ENTOLITE (PETN/TNT,50/50)

WEIGHT OF CHARGE LBS	PEAK PRESSURE PSI	POSITIVE DURATION MILLISEC	PULSE LENGTH PSI	YIELD TIME MSEC	MAXIMUM DEFORMATION STRESS PSI	TIME MSEC	DEFLEC-TION INCH	STRAIN IN/IN	RESIDUAL DEFLEC-TION INCH	DEFORM STRAIN IN/IN	OXIDATION LAST PRODUCT	PERCENT	CONFINED EXPLOSION GAS PRES. PSI	EXPLOSIVE GAS STRESS PSI
2.000	1792.	.136	.120*********		14022.	.196	.0102	.00034	0.0000	0.00000	COMPLETE	0.0	206.	2193.
IMPULSE =	121.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6005.	DEG R
2.518	2122.	.137	.121*********		16809.	.196	.0123	.00041	0.0000	0.00000	COMPLETE	0.0	248.	2640.
IMPULSE =	146.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6705.	DEG R
3.170	2507.	.140	.124*********		20076.	.196	.0147	.00049	0.0000	0.00000	CO2	80.9	280.	2980.
IMPULSE =	175.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6791.	DEG R
3.991	2940.	.144	.128*********		23970.	.196	.0175	.00058	0.0000	0.00000	CO2	61.4	315.	3349.
IMPULSE =	211.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6717.	DEG R
5.024	3423.	.149	.133*********		28630.	.197	.0209	.00070	0.0000	0.00000	CO2	46.0	358.	3811.
IMPULSE =	255.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6644.	DEG R
6.325	3960.	.155	.139*********		34197.	.198	.0250	.00083	0.0000	0.00000	CO2	33.7	413.	4392.
IMPULSE =	308.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6572.	DEG R
7.962	4553.	.163	.146*********		40835.	.200	.0298	.00099	0.0000	0.00000	CO2	23.9	481.	5122.
IMPULSE =	372.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6503.	DEG R
10.024	5205.	.173	.154*********		48726.	.202	.0356	.00119	0.0000	0.00000	CO2	16.2	568.	6039.
IMPULSE =	451.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6439.	DEG R
12.619	5920.	.185	.164*********		58075.	.205	.0424	.00141	0.0000	0.00000	CO2	10.0	676.	7191.
IMPULSE =	548.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6380.	DEG R
15.887	6703.	.199	.175*********		69098.	.208	.0504	.00168	0.0000	0.00000	CO2	5.1	812.	8641.
IMPULSE =	666.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6328.	DEG R
20.000	7558.	.215	.187	.191	80085.	.212	.0599	.00200	.0015	.00005	CO2	1.3	984.	10464.
IMPULSE =	811.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6283.	DEG R
25.179	8491.	.233	.200	.157	80047.	.226	.0725	.00242	.0141	.00047	CO	98.2	1205.	12821.
IMPULSE =	989.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6331.	DEG R
31.698	9509.	.254	.214	.140	80108.	.249	.0908	.00303	.0323	.00108	CO	95.7	1488.	15828.
IMPULSE =	1208.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6422.	DEG R
39.905	10619.	.278	.230	.127	80199.	.282	.1182	.00394	.0597	.00199	CO	93.8	1844.	19612.
IMPULSE =	1479.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6498.	DEG R
50.238	11831.	.306	.247	.117	80342.	.330	.1609	.00536	.1023	.00341	CO	92.2	2291.	24373.
IMPULSE =	1812.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6561.	DEG R
63.246	13153.	.338	.265	.108	80573.	.401	.2302	.00767	.1714	.00571	CO	91.0	2854.	30366.
IMPULSE =	2225.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6613.	DEG R
79.621	14596.	.375	.283	.101	80973.	.512	.3502	.01167	.2911	.00970	CO	90.0	3563.	37908.
IMPULSE =	2736.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6656.	DEG R
100.237	16172.	.417	.302	.094	81743.	.706	.5813	.01938	.5216	.01739	CO	89.2	4456.	47401.
IMPULSE =	3370.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6690.	DEG R
126.191	17896.	.465	.320	.088	83565.	1.122	1.1278	.03759	1.0668	.03556	CO	88.6	5579.	59352.
IMPULSE =	4157.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6718.	DEG R

```
4 158.866  19781.       .519     .336     .083    90813.  2.309  3.8623    .10208    2.9966   .89989        CO  88.1    6993.      74396.
IMPULSE =    5135. PSI-MSEC                                                         EXPLOSIVE GAS TEMPERATURE =     6741. DEG R
4 200.000  21845.       .582     .348     .079   114537.  4.209 10.4195    .34732   10.3358   .34453        CO  87.8    8773.      93334.
IMPULSE =    6354. PSI-MSEC                                                         EXPLOSIVE GAS TEMPERATURE =     6759. DEG R
4 251.785  24106.       .653     .355     .074   158558.  4.997 23.6258    .78753   23.5101   .78367        CO  87.4   11014.     117175.
IMPULSE =    7874. PSI-MSEC                                                         EXPLOSIVE GAS TEMPERATURE =     6773. DEG R
```

VESSEL DIAMETER = 5.00 FEET, WALL THICKNESS = 1.520 INCHES

METAL PROPERTIES DENSITY = .283 LBS/CU.IN. MODULUS = .300E+08 PSI
POISSONS RATIO = .270 WORK HARDENING
YIELD STRENGTH = 80000. PSI COEFFICIENT = 100000. PSI

ATMOSPHERIC CONDITIONS PRESSURE = 14.7 PSI TEMPERATURE = 25. DEG CENTIGRADE

ENTOLITE (PETN/TNT,50/50)

WEIGHT OF CHARGE LBS	PEAK PRESSURE PSI	POSITIVE DURATION MILLISEC	PULSE LENGTH PSI	YIELD TIME MSEC	MAXIMUM DEFORMATION STRESS PSI	TIME MSEC	DEFLEC-TION INCH	STRAIN IN/IN	RESIDUAL DEFLEC-TION INCH	DEFORM STRAIN IN/IN	OXIDATION LAST PRODUCT	PERCENT	CONFINED EXPLOSION GAS PRES. PSI	EXPLOSIVE GAS STRESS PSI
2.000	1782.	.136	.120	********	13008.	.196	.0095	.00032	0.0000	0.00000	COMPLETE	0.0	206.	2034.
IMPULSE =	121.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6005.	DEG R
2.518	2122.	.137	.121	********	15593.	.196	.0114	.00038	0.0000	0.00000	COMPLETE	0.0	248.	2449.
IMPULSE =	146.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6705.	DEG R
3.170	2507.	.140	.124	********	18623.	.196	.0136	.00045	0.0000	0.00000	CO2	80.9	280.	2764.
IMPULSE =	175.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6791.	DEG R
3.991	2940.	.144	.128	********	22236.	.196	.0162	.00054	0.0000	0.00000	CO2	61.4	315.	3106.
IMPULSE =	211.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6717.	DEG R
5.024	3423.	.149	.133	********	26558.	.197	.0194	.00065	0.0000	0.00000	CO2	46.0	358.	3535.
IMPULSE =	255.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6644.	DEG R
6.325	3960.	.155	.139	********	31722.	.198	.0232	.00077	0.0000	0.00000	CO2	33.7	413.	4074.
IMPULSE =	308.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6572.	DEG R
7.962	4553.	.163	.146	********	37879.	.200	.0277	.00092	0.0000	0.00000	CO2	23.9	481.	4751.
IMPULSE =	372.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6503.	DEG R
10.024	5205.	.173	.154	********	45200.	.202	.0330	.00110	0.0000	0.00000	CO2	16.2	568.	5602.
IMPULSE =	451.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6439.	DEG R
12.619	5920.	.185	.164	********	53877.	.205	.0393	.00131	0.0000	0.00000	CO2	10.0	676.	6671.
IMPULSE =	548.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6380.	DEG R
15.887	6703.	.199	.175	********	64098.	.208	.0469	.00156	0.0000	0.00000	CO2	5.1	812.	8015.
IMPULSE =	666.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6328.	DEG R
20.000	7558.	.215	.187	********	76089.	.212	.0555	.00185	0.0000	0.00000	CO2	1.3	984.	9706.
IMPULSE =	811.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6283.	DEG R
25.179	8491.	.233	.200	.170	80026.	.221	.0663	.00221	.0079	.00026	CO	98.2	1205.	11893.
IMPULSE =	989.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6331.	DEG R
31.698	9509.	.254	.214	.148	80077.	.240	.0816	.00272	.0231	.00077	CO	95.7	1488.	14683.
IMPULSE =	1208.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6422.	DEG R
39.905	10619.	.278	.230	.134	80153.	.268	.1042	.00347	.0457	.00152	CO	93.8	1844.	18193.
IMPULSE =	1479.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6498.	DEG R
50.238	11831.	.306	.247	.123	80268.	.309	.1388	.00463	.0802	.00267	CO	92.2	2291.	22610.
IMPULSE =	1812.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6561.	DEG R
63.246	13153.	.338	.265	.113	80452.	.369	.1939	.00646	.1351	.00450	CO	91.0	2854.	28168.
IMPULSE =	2225.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6613.	DEG R
79.621	14596.	.375	.283	.105	80761.	.461	.2866	.00955	.2276	.00759	CO	90.0	3563.	35164.
IMPULSE =	2736.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6656.	DEG R
100.237	16172.	.417	.302	.098	81329.	.613	.4571	.01524	.3977	.01326	CO	89.2	4456.	43971.
IMPULSE =	3378.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6690.	DEG R
126.191	17896.	.465	.320	.092	82561.	.917	.8266	.02755	.7664	.02555	CO	88.6	5579.	55056.
IMPULSE =	4157.	PSI-MSEC								EXPLOSIVE	GAS TEMPERATURE =		6718.	DEG R

```
4 158.866  13781.      .519    .336     .087   86330.  1.730  1.9574   .06525   1.8943   .06314        CO  88.1   6993.      69012.
IMPULSE =   5135. PSI-MSEC                                                                EXPLOSIVE GAS TEMPERATURE =      6741. DEG R
4 200.000  21845.      .582    .348     .082  103110.  3.719  6.9914   .23305   6.9162   .23054        CO  87.8   8773.      86579.
IMPULSE =   6354. PSI-MSEC                                                                EXPLOSIVE GAS TEMPERATURE =      6759. DEG R
4 251.785  24106.      .653    .355     .077  141924.  4.865 18.6356   .62119  18.5320   .61773        CO  87.4  11014.     108695.
IMPULSE =   7874. PSI-MSEC                                                                EXPLOSIVE GAS TEMPERATURE =      6773. DEG R
```

APPENDIX B

REINFORCING RING DESIGN

REINFORCING RING DESIGN

General Criteria

The design formulas for the reinforcing ring and door were derived using an average wall thickness of the vessel and the following constraints:

- The formulas were based upon a static internal pressure loading.
- The sphere was assumed to act as a thin shell, which is completely valid only for shells having a ratio between the radius to the median surface and the thickness greater than or equal to 60 ($a_s/t_s > 60$). The stress in the shell was then given by the following formula:

$$\sigma_s = pa_s/2t_s \tag{B-1}$$

where

σ_s = uniform stress in the sphere
p = static internal pressure
a_s = radius to the median surface of the sphere
t_s = thickness of the spherical shell.

- The door was designed to a stress at the outer surface of the center of the door equal to that in the sphere so that gross deformation and subsequent shifting of the bearing support line with the ring would not occur.
- The ring was designed so that the sphere and the ring would have equal static deflection at their welded junction under an internal pressure.
- All eccentricities within the ring and sphere junction were minimized for a static loading.

The average wall thickness of the vessels was used even though there was a significant variation in true wall thickness from the center to the edge of each hemisphere because it was both conservative and the best number available so that the design could proceed before the hemispheres were delivered.

It is noted that obtaining reliable actual wall-thickness information from suppliers of formed hemispheres is not an easy matter. Formed hemispheres are characteristically supplied for pressure-vessel applications in which the minimum wall thickness is the applicable criteria. With the uncontrollable variations in wall thickness which occur during the forming operation, manufacturers characteristically use an appreciable extra thickness for the original blank to insure that the quoted minimum is exceeded at the thinnest portion of the final fabrication, since weight is not normally a factor in pressure-vessel applications. In this work, however, minimum weight is one of the primary considerations. For purposes of determining the average wall thickness which will be realized in a vessel, the manufacturer's quoted inside diameter and estimated (not guaranteed) shipping weight seems to provide the best indication of what the average wall thickness of the vessel is likely to be for design purposes. Consideration must be given to the expected minimum wall thickness as well, since the hot-spinning process, for example, appears to lead to much larger and more uncontrollable variations in wall thickness than hot pressing in a die.

Steps in Design

This section includes the design guidelines developed for the vessels fabricated in this program. The performance of the vessels tested to date using these guidelines appears to be generally satisfactory, although additional experience with them is desirable before they can be regarded as firmly established. The vessels fabricated for this program were not sized with the intention of containment of a specified blast load, since no design criteria for this purpose existed at the inception of this program. However, the results of this research now allow choice of a vessel diameter and wall thickness expected to accomplish a specific containment objective. In addition, the size of the opening desired is selected on the basis of the expected end use of the vessel. Currently, our judgment for most applications is that the port opening should not exceed the radius of the vessel.

Figure (B-1) illustrates the geometry of the junction between the sphere, reinforcing ring and door.

The size of the bearing surface b between the ring and the door is the first quantity to be determined. For a first estimate, the following expression was used:

$$b = (\sigma_s/\sigma_b)(a_d/a_s)t_s \quad , \tag{B-2}$$

where

σ_b = the lower of the compressive yield-stress values for the door and ring materials.

a_d = radius of the port.

The remaining quantities were defined in Equation (B-1). The value of b was then refined using the following formula wherein a_o was substituted for a_d:

$$a_o = a_d + b/2 \tag{B-3}$$

$$b = (\sigma_s/\sigma_b)(a_o/a_s)t_s, \tag{B-4}$$

where

a_o = approximate location of the bearing stress load line assuming c is equal to zero in Figure (B-1).

The thickness of the flat plate door, t_d, was determined from the following formula for small deflections, which considers not only bending of the plate but also shearing strain and lateral pressure effects on the edge of the door.

$$t_d = \left[\frac{3}{4} (3 + \nu)\, a_o^{\,2}/(a_s/t_s - \frac{1}{2} (\frac{3 + \nu}{1 - \nu})) \right]^{1/2} , \tag{B-5}$$

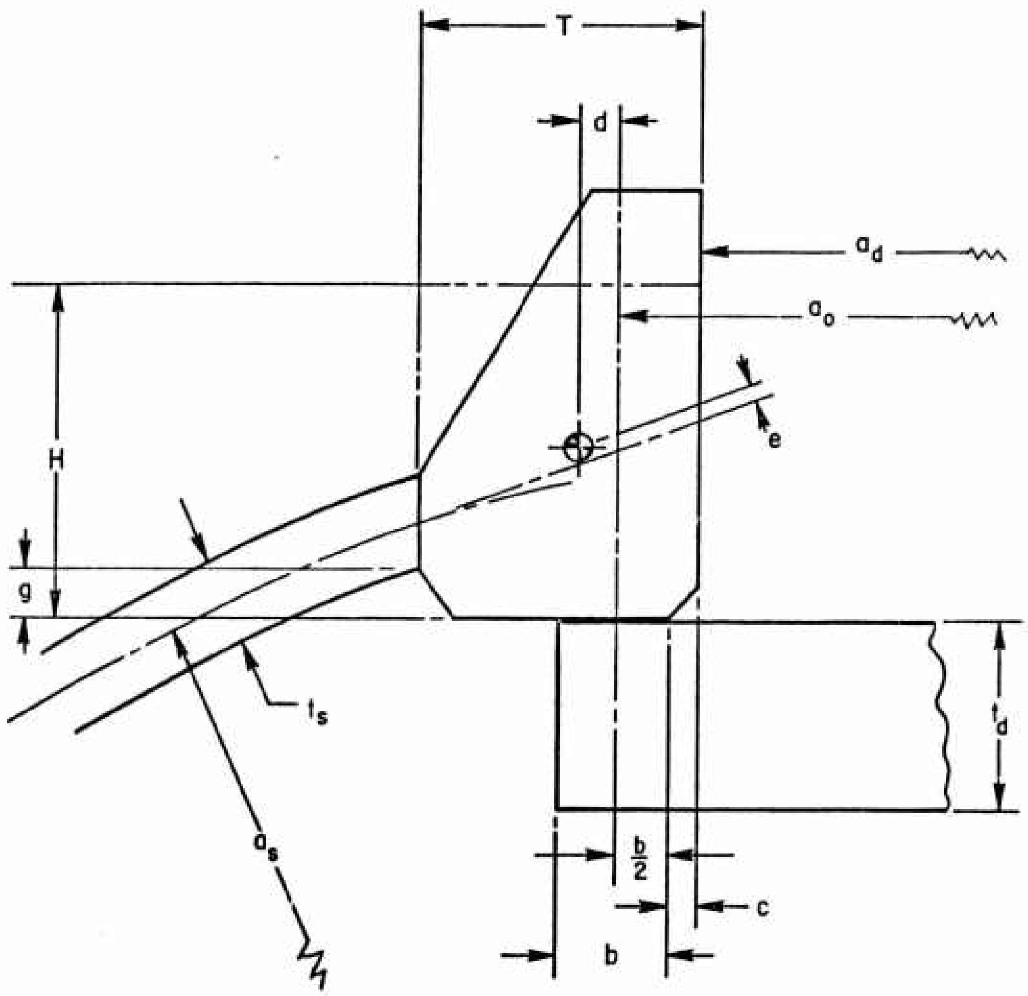


FIGURE 1. GEOMETRY OF THE JUNCTION BETWEEN THE SPHERE, REINFORCING RING, AND DOOR

where ν is Poisson's Ratio ($\nu = 0.27$ for steel). The objective in the design of the door was to provide a part that would support both the dynamic load and the static load of a contained explosion without deforming so much that the load line geometry between the door and the ring was destroyed. The stress found in the sphere was used as the maximum value of stress to be found in the door. This occurred at the outer surface of the center of the door.

The first approximation of the reinforcing-ring cross section was generated with the assumption that the centroid of the ring would lie close to the radius, a_o. The following formula, which was derived for a thin ring, which has a thickness-to-radius ratio less than 1:5, and a sphere, was used for the first estimate of the cross section of the ring, which would deform the same amount at its centroid as the sphere, if the sphere had continued to the same location:

$$A = \frac{a_s t_s}{(1-\nu)} \cos \phi_o \sin \phi_o, \tag{B-6}$$

where

$$\phi_o = \sin^{-1}(a_o/a_s). \tag{B-7}$$

This rectangular area, A, Then allowed a reasonable engineering estimate for the thickness of the ring, T, to be made. If the ratio, T/a_o, violated the thin-ring criterion, the following formula, based on a thick ring with the deflection matched at the point of contact with the hemisphere, was used to determine the height, H, of the ring:

$$H = \frac{2E_s t_s}{E_r(1-\nu)} \left[\frac{\sqrt{a_s^2 - (a_d + T)^2}}{2} - g \right] \frac{1}{a_s} \left[\frac{1 + (1 + \frac{T}{a_d})^2}{(1 + \frac{T}{a_d})^2 - 1} - \nu \right] \tag{B-8}$$

where E_r and E_s are Young's Modulus of the ring and sphere, respectively, and the other quantities are as shown in Figure (B-1). The area and the rough dimensions of T and H are next represented on a drawing, such as Figure (B-1). Using this drawing, the shape of the ring cross section was changed from simply rectangular to accomplish the following two objectives while keeping the cross-sectional area, A, of the ring constant:

- Make the transition or change in cross section between the sphere and the ring as smooth as possible to avoid large stress concentrations.
- Make the sum of the moments caused by the bearing load from the door and the loading by the sphere as near equal to zero about the centroid of the ring cross section as possible, to minimize the tendency of the ring to twist under load.

The second objective was expressed by the equation:

$$e = d \frac{a_o}{a_s} \qquad \text{(B-9)}$$

where

e = perpendicular distance from the projected load line from the junction of the sphere and ring to the centroid of the ring.

d = perpendicular distance from the projected door/ring bearing line to the centroid of the ring.

A rapid solution for the ring sizes and shapes required for cost and sizing purposes was facilitated by adjusting a_o through use of the internal chamfer, c, on the inside surface of the ring (see Figure (B-1)).

$$a_o = a_d + c + b/2. \qquad \text{(B-10)}$$

The final iteration checked the validity of the values calculated for the bearing surface, door thickness, cross section of the reinforcing ring, and the balance of the moments about the centroid of the reinforcing ring.

APPENDIX C

WELDING PROCEDURE SPECIFICATIONS

WELDING PROCEDURE SPECIFICATION (WPS)

Welding Procedure Specification No./ Revisions P-74-A

Date 12/3/74 Supporting PQR No(S) PQ-74-1

Welding Process(es) Gas Metal Arc in combination with shielded metal arc

Types Semi-Automatic (GMA) and Manual (SMA)

JOINTS

Groove design Single U

Backing

Other

BASE METAL

P No. 1 to P No. 1

Thickness range 3/16" to 3"

Other

FILLER METALS

F No. 4 and 6 Other

A No. 1 Other

Spec. No. SFA 5.5 / SFA 5.18 (SFA, SFB) AWS No. E8016-C3 / E70 S-4 (Class)

Size of Electrode E8016 1/8" dia. / E70 S-4 0.045" dia.

Size of Filler

Flux Composition

Particle Size

Electrode Flux Composition

Consumable Insert

Other

POSITION

Position of Groove Flat

Welding progression

Other

PREHEAT

Preheat Temp. 250 F min.

Interpass Temp. 250 F min.

Preheat Maintenance

Other

POSTWELD HEAT TREATMENT

Temperature

Time Range

Other

WELDING PROCEDURE SPECIFICATION (WPS)
(Continued)

Welding Procedure Specification No. P-74-A Date 12-3-74

GAS

Shielding Gas(es) Argon - 2% Oxygen

Percent Composition ____________
(mixtures)

Flow Rate 55 cfh

Gas Backing ____________

Trailing Shielding
Gas Composition ____________

Other ____________

ELECTRICAL CHARACTERISTICS

Current DC (AC or DC) Polarity Reverse

Amps. 250-290 GMA (Range) Volts 26-28 GMA (Range)

Travel Speed 7 to 11 ipm (Range)

Other ____________

____

TECHNIQUE PROCEDURES

String or Weave Bead String

Orifice or Gas Cup Size ____________

Initial & Interpass Cleaning Initial: hand-held power grinder. Interpass: powered wire brush

Method of Back Gouging Power Grinder

____

Oscillation ____________

Contact Tube to Work Distance 3/8"

Multipass or Single Pass Multipass
(per side)

Single or Multiple Electrodes Single

Other ____________

____

____

PROCEDURE QUALIFICATION RECORD (PQR)

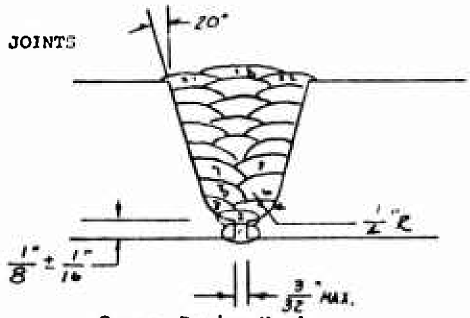
Procedure Qualification Record No. PQ-74-1 Date Dec. 4, 1974

WPS No. P-74-A

Welding Process(es) Shielded metal-arc for passes 1 and 2, gas metal-arc for balance.

Types Semi-Auto(SMA)&Manual(SMA)
(Manual, Automatic, Semi-Auto.)

JOINTS



Groove Design Used

BASE METALS

Material Spec. A537A
Type or Grade
P No. 1 to P No. 1
Thickness 1½ inches
Diameter
Other

FILLER METALS

Weld Metal Analysis A No. 1
Size of Electrode 1/8" covered electrode; 0.045" wire
Filler Metal F No. 4(covered electrode); 6(wire)
SFA Specification 5.5 and 5.18
AWS Classification E8016-C3 and E705-4
Other

POSITION

Position of Groove Flat
Weld Progression
(Uphill, Downhill)
Other

PREHEAT

Preheat Temp. 250F
Interpass Temp. 250F
Other

POSTWELD HEAT TREATMENT

Temperature
Time
Other

GAS

Type of Gas or Gases Argon-2%O2
& Composition of Gas Mixture
Other 55 cfh

ELECTRICAL CHARACTERISTICS

Current DC
Polarity Reverse
Amps. 170(SMA) 200(GMA) Volts 27 (GMA)
Travel Speed 7 ipm (passes 3-18); 11ipm (balance)
Other

TECHNIQUE PROCEDURES

String or Weave Bead String
Oscillation
Multipass or Single Pass Multiple (per side)
Single or Multiple Electrodes Single

PROCEDURE QUALIFICATION RECORD (PQR) PQ-74-1 12/4/74
(Continued)

TENSILE TEST RESULTS
SPECIMEN DIMENSIONS PER FIGURE QW 462.1d, Section IX, ASME Boiler Code

Specimen Number	Dimensions Width (1)	Thickness (2)	Area sq. in.	Ultimate Load, lb	Stress, psi	Character and Location of Failure
1	0.504 inch diameter		0.199	15,780	79,200	Weld metal
2	0.503 " "		0.198	15,050	76,100	" "
3	0.503 " "		0.198	15,390	77,700	" "
4	0.504 " "		0.199	15,210	76,600	" "

(1) Record outside diameter if a full pipe section is tested.
(2) Record wall thickness if a full pipe section is tested.

GUIDED BEND TEST RESULTS
SPECIMEN DIMENSIONS PER FIGURE QW 462.2a Section IX, ASME Boiler Code

Specimen Number	Type	Bend Radius	Results	Specimen Number	Type	Bend Radius	Results
1	Side	1-1/4"	No defects	4	Side	1-1/4"	No defects
2	Side	1-1/4"	No defects				
3	Side	1-1/4"	No defects				

Toughness Tests

Specimen No.	Notch Location	Notch Test Type	Notch Test Temp.	Impact Values	Lateral Exp. %Shear	Lateral Exp. Mils	Drop Weight Break	Drop Weight No Break

Type of Test ______________________
Deposit Analysis ______________________
Other ______________________

Fillet Weld Test

Result - Satisfactory ________ (Yes, No)
Penetration into Parent Metal ________ (Yes, No)

Type and Character of Failure ________
Macro Results ________

Remarks

The results of the bend and tensile tests meet the requirements of Section IX, ASME Boiler and Pressure Vessel Code, 1974.

Weld made by W. H. Stefanov

WELDING PROCEDURE SPECIFICATION (WPS)

Welding Procedure Specification No/ Revisions P-75-A | Date 3/28/75 | Supporting PQR No(S) PQ-75-1

Welding Process(es) Gas-metal-arc in combination with shielded metal arc | Types Semi-automatic (GMA and Manual (SMA)

JOINTS

Groove design Single U

Backing

Other

BASE METALS

P No. 1 to P No. 1

Thickness range 3/16" to 3"

Other

FILLER METALS

F No. 4 and 6 Other

A No. 1 Other

Spec. No. SFA 5.5 / SFA 5.20 / SFA, SFB AWS No. E7018 / E70T-1 Class

Size of Electrode E7018 - 1/8" dia. / E70T-1 - 3/32" dia.

Size of Filler

Flux Composition

Particle Size

Electrode Flux Composition

Consumable Insert

Other

POSITION

Position of Groove Flat

Welding progression

Other

PREHEAT

Preheat Temp. 250 F min.

Interpass Temp. 250 F min.

Preheat Maintenance

Other

POSTWELD HEAT TREATMENT

Temperature

Time Range

Other

WELDING PROCEDURE SPECIFICATION (WPS)
(Continued)

Welding Procedure Specification No. P-75-A Date 3/28/75

GAS

Shielding Gas(es) Carbon dioxide

Percent Composition ______ (mixtures)

Flow Rate 50 cfh

Gas Backing ______

Trailing Shielding Gas Composition ______

Other ______

ELECTRICAL CHARACTERISTICS

Current DC (AC or DC) Polarity Reverse

Amps. E7018 160 to 180, E70T-1 380-400 (Range) Volts 26 volts E70T-1 (Range)

Travel Speed ______ (Range)

Other ______

TECHNIQUE PROCEDURES

String or Weave Bead String

Orifice or Gas Cup Size ______

Initial & Interpass Cleaning Initial: hand-held power grinder; Interpass: powered wire brush

Method of Back Gouging Power grinder

Oscillation ______

Contact Tube to Work Distance ______

Multipass or Single Pass Multipass (per side)

Single or Multiple Electrodes Single

Other ______

PROCEDURE QUALIFICATION RECORD (PQR)

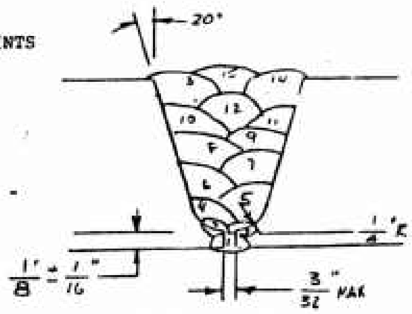
Procedure Qualification Record No. PQ-75-1 **Date** 3/28/75

WPS No. P-75-A

Welding Process(es) Shielded metal-arc for passes 1 thru 3, gas metal-arc for balance

Types Semi-Auto (GMA) and Manual (SMA)
(Manual, Automatic, Semi-Auto.)

JOINTS



Groove Design Used

BASE METALS

Material Spec. A537A
Type or Grade
P No. 1 to P No. 1
Thickness 1-1/2 inches
Diameter
Other

FILLER METALS

Weld Metal Analysis A No. 1
Size of Electrode E7018 1/8"; E70T-1 3/32"
Filler Metal F No. 4 and 6
SFA Specification 5.5 and 5.20
AWS Classification E7018 and E70T-1
Other

POSITION

Position of Groove Flat
Weld Progression
(Uphill, Downhill)
Other

PREHEAT

Preheat Temp. 250 F
Interpass Temp. 250 F
Other

POSTWELD HEAT TREATMENT

Temperature
Time
Other

GAS

Type of Gas or Gases Carbon dioxide
& Composition of Gas Mixture
Other 50 cfh

ELECTRICAL CHARACTERISTICS

Current DC
Polarity Reverse
Amps. * Volts 26 volts - E70T-1
Travel Speed
Other

TECHNIQUE PROCEDURES

String or Weave Bead String
Oscillation
Multipass or Single Pass Multiple (per side)
Single or Multiple Electrodes Single

* 170 amps 7018
380-400 amps E70T-1

PROCEDURE QUALIFICATION RECORD (PQR) PQ-75-1 3/28/75
(Continued)

TENSILE TEST RESULTS
SPECIMEN DIMENSIONS PER FIGURE QW 462.1d, Section IX, ASME Boiler Code

Specimen Number	Dimensions Width (1)	Dimensions Thickness (2)	Area sq. in.	Ultimate Load, lb	Stress, psi	Character and Location of Failure
1			0.202	16,025	79,406	Weld metal
2			0.202	15,925	78,880	Base metal
3			0.200	16,000	79,880	Base metal
4			0.201	15,750	78,511	Base metal

(1) Record outside diameter if a full pipe section is tested.
(2) Record wall thickness if a full pipe section is tested.

GUIDED BEND TEST RESULTS
SPECIMEN DIMENSIONS PER FIGURE QW 452.2a, Section IX, ASME Boiler Code

Specimen Number	Type	Bend Radius	Results	Specimen Number	Type	Bend Radius	Results
1	Side	1-1/4"	No defects	4	Side	1-1/4"	No defects
2	Side	1-1/4"	No defects				
3	Side	1-1/4"	No defects				

Toughness Tests

Specimen No.	Notch Location	Notch Test Type	Notch Test Temp.	Impact Values	Lateral Exp. % Shear	Lateral Exp. Mils	Drop Weight Break	Drop Weight No Break

Type of Test ______________________
Deposit Analysis ______________________
Other ______________________

Fillet Weld Test

Result - Satisfactory ________ Yes, No **Penetration into Parent Metal** ________ Yes, No

Type and Character of Failure ________ **Macro Results** ________

Remarks

The results of the bend and tensile tests met the requirements of Section IX, ASME Boiler and Pressure Vessel Code, 1974. Welds made by W.H. Stefanov.

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